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SEASONAL CHANGES IN THE SURFACE WATER MASSES AND IN THEIR PLANKTON IN THE BERMUDA AREA

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ABSTRACT

Bermuda plankton studies showed seasonal differences in the fauna which suggested different origins of the water in summer and winter. Studies of the geographical distribution of typical summer and winter species confirmed this, showing widely different centers of distribution for the two seasonal groups. Previous studies of currents and of the distributions of temperature and transparency suggested an eddy of the Gulf Stream, reaching Bermuda from the east or southeast. The present current studies confirm the indications of the plankton distribution in showing that Bermuda summer water comes from the North Equatorial Current, while the winter water comes from an eddy of the Gulf Stream approximately along the 30° parallel.

In an earlier study of the zooplankton of the Bermuda area (Moore, 1949), it was shown that the plankton was distinctly different in summer and winter. There was a sharp transition in October, and a second, less well defined, in late winter or spring. The change was apparent in the species comprising the zooplankton, in the number of species present, and in the total volume of plankton per standard haul at a single station. These changes are shown in Figure 1. The volume changes at a single station were shown to be due to a shift in the position of a plankton-rich area which lay to the east of the islands in summer and to the west in winter. This shift strongly suggested a change in the circulation system around the island, which was borne out by the nature of the summer and winter faunas.

¹Contribution No. 677 from the Woods Hole Oceanographic Institution.
Contribution No. 206 from the Bermuda Biological Station.
Contribution No. 113 from the Marine Laboratory, University of Miami.

It was hoped that some of the typically summer and winter zooplankton species might be used as indicators of the origin of their respective water masses, and with this in view, a study of the Atlantic

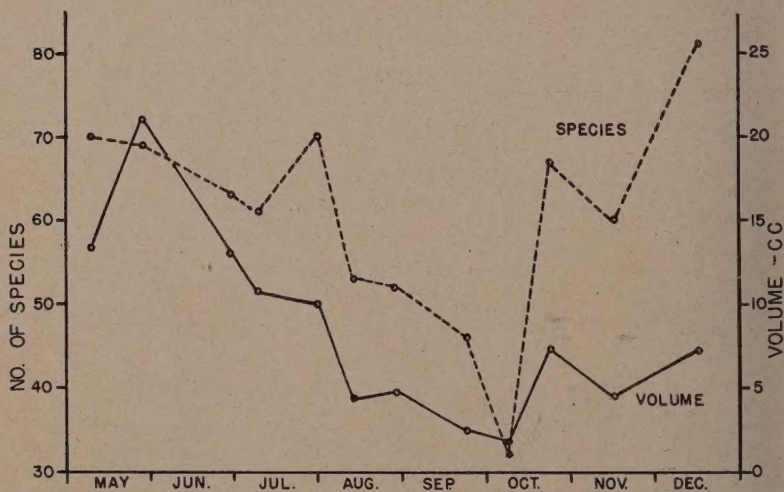


FIGURE 1. Seasonal variation in number of species present and in size of catch at a standard station off Bermuda.

distribution of a series of selected forms was commenced in 1947. The study was begun at the Woods Hole Oceanographic Institution and later continued at the Marine Laboratory of the University of Miami. At the latter, Hela undertook a study of the seasonal surface drift of the Bermuda area, which was part of a more general survey of the North Atlantic (Hela, 1954).

ZOOPLANKTON STUDIES

The following species, all of which showed marked seasonal fluctuation in numbers at Bermuda, were selected as possible indicator forms:

SUMMER SPECIES

Diphyes dispar Chamisso & Eysenhardt

WINTER SPECIES

SIPHONOPHORA

Diphyes bojani (Eschscholtz)
Eudoxoides spiralis (Bigelow)
Abylopsis eschscholtzii Huxley
A. tetragona Otto
Bassia bassensis (Quoy & Gaimard)

CHAETOGNATHA

Sagitta bipunctata Quoy & Gaimard
S. hexaptera D'Orbigny
S. lyra Krohn

Sagitta planktonis Steinhaus
Pterosagitta draco (Krohn)
Krohnitta subtilis (Grassi)

The groups chosen were limited to those with widespread records from the North Atlantic. Unfortunately these did not include the Pteropoda, which otherwise would have been ideal. Also a considerable series of hauls, referred to below and examined by us, had not been properly preserved. Their examination was delayed by World

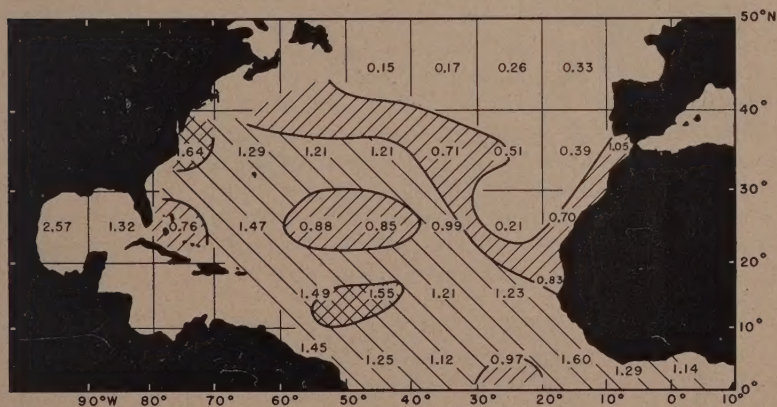


FIGURE 2. Distribution of species typical of Bermuda waters in winter.

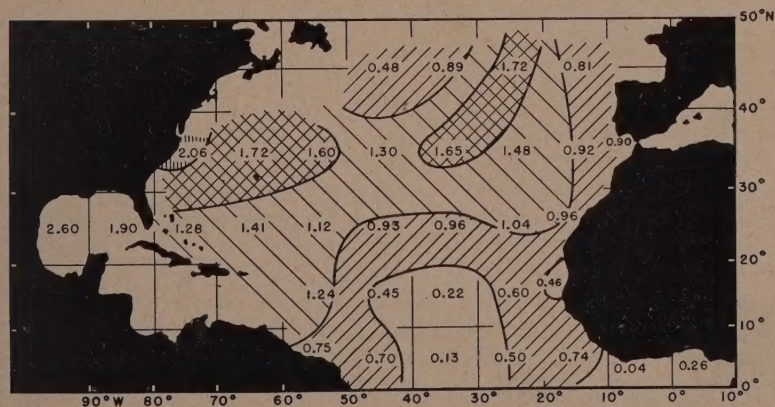


FIGURE 3. Distribution of species typical of Bermuda waters in summer.

War II, and after a lapse of several years they had become decalcified and many of the pteropods were no longer identifiable. However, the larger pteropods did provide verification for the belief that the seasonal changes mentioned above recurred in successive years. In material collected by Dr. M. V. Lebour in the summer of 1947, they were very scarce, as they had been in the summers previously studied. These appear to be typically winter forms in Bermuda.

Abstracts were made from the published records of all expeditions which have worked in the North Atlantic². They were grouped by 10° squares, and presence or absence of each of the selected species was noted. The percentage occurrence of each species was then calculated for each square. Allowance was made for the varying relative total abundance of the different species by weighing each value in proportion to the total number of records of the species for the whole area. Finally, for each 10° square, a mean value was obtained for the combined winter forms, and for the combined summer forms. Figures 2 and 3 show these values, expressed in arbitrary units, and it is clear that those species which are common in Bermuda waters in winter have characteristically different distributions from those common in summer.

These two charts indicate the centers of abundance of the Bermuda summer and winter forms. However, at these centers, the species in question may occur more abundantly than they do in the Bermuda area at the appropriate season. An attempt was therefore made to locate the areas where the frequency of occurrence most closely approximated that found around Bermuda. It would have been desirable to separate the published data into two groups according to whether the hauls were made in summer or winter, omitting those made in the transition periods, but this would have reduced the available data unduly. The best that could be done was to determine those areas in which mean annual conditions most closely approximated those found in the Bermuda area in summer and winter respectively. For the Bermuda area, sufficient seasonal data were already available. The results (Figure 4) show that Bermuda winter conditions are most closely matched by a band of water lying well to the south of the islands, and extending from the West Indies across to the African coast at approximately 20° north latitude. Summer conditions are most closely matched by a band of water lying roughly along the course of

²Bedot, 1904; Bigelow, 1918; Burfield, 1930; Chun, 1897; Fowler, 1906; Germain and Joubin, 1916; Haeckel, 1888; Leloup, 1933; Leloup and Hentschel, 1935; Moser, 1925; Ritter-Zahony, 1911, 1911a; Thiel, 1938; Totton, 1936.

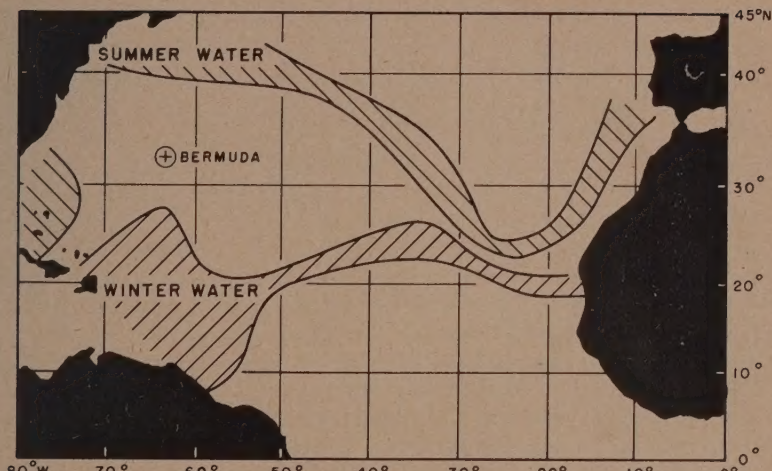


FIGURE 4. Centers of distribution of Bermuda summer and winter species.

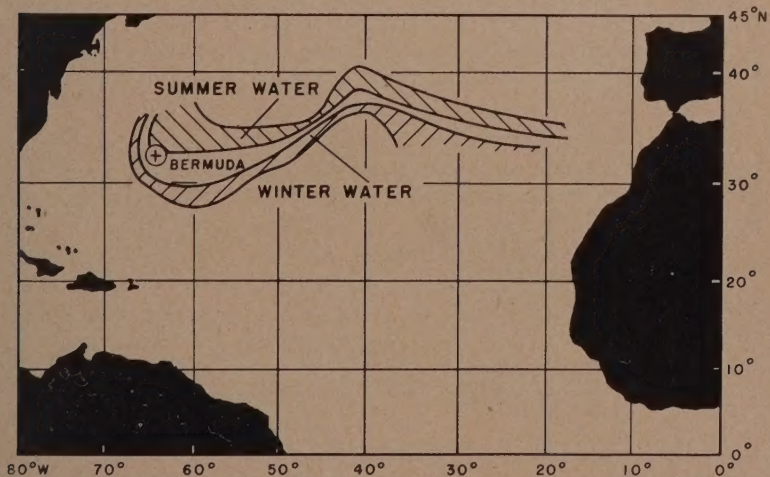


FIGURE 5. Areas most closely approximating Bermuda summer and winter conditions.

the Gulf Stream from Florida to the northeast of Bermuda, and swinging southward to the east.

Most of the expedition reports give records of presence or absence,

but do not include counts of the relative abundance of the different species. The latter give a far more reliable picture of distribution, but are available for only a limited series of stations. In order to extend these data, the *Atlantis* has collected plankton samples, usually night surface hauls, on a number of cruises extending widely over the North Atlantic. The siphonophores and chaetognaths have been counted in all of these hauls. For each selected siphonophore species, a value was calculated expressing its numerical abundance as a percentage of the total summer siphonophore population in the Bermuda area. A winter value was obtained in the same way. Similarly, the chaetognaths were expressed as percentages of the total chaetognath population. Finally, weighted values which expressed the typical ratio of total summer to total winter forms in the area in each season were obtained. The ratio of Bermuda summer species to winter species was calculated in the same way for those parts of the North Atlantic where these species occurred and a chart of the distribution of this ratio was prepared. From this, the areas in which the annual mean values most closely approximate Bermuda summer and winter conditions, respectively, were determined and are shown in Figure 5. There is some resemblance between these and the areas indicated from other data in Figure 4, but in this case the two areas lie considerably closer together.

Both methods indicated that the water masses whose plankton most closely corresponded with Bermuda summer and winter conditions lie respectively further north and further south. The fact that mean annual plankton, rather than appropriate seasonal plankton, was compared, has masked any possible seasonal change within these areas, but their separation is still marked. However, both areas extend for a considerable distance, more or less along the line of flow of the Gulf Stream. It has not, therefore, been possible to associate any very circumscribed area with the Bermuda plankton. Such information must be sought in a study of the current system.

CURRENT SYSTEMS

Bermuda lies well to the east of the Gulf Stream system and within the Sargasso Sea, but there are some indications that it may, at least on occasions, be influenced by an eddy of the main stream. Iselin (1936) has indicated the existence of such an eddy in a generalized way (Figure 6). Fuglister (personal communication) has prepared charts showing the distribution of temperature (Figure 7) and salinity

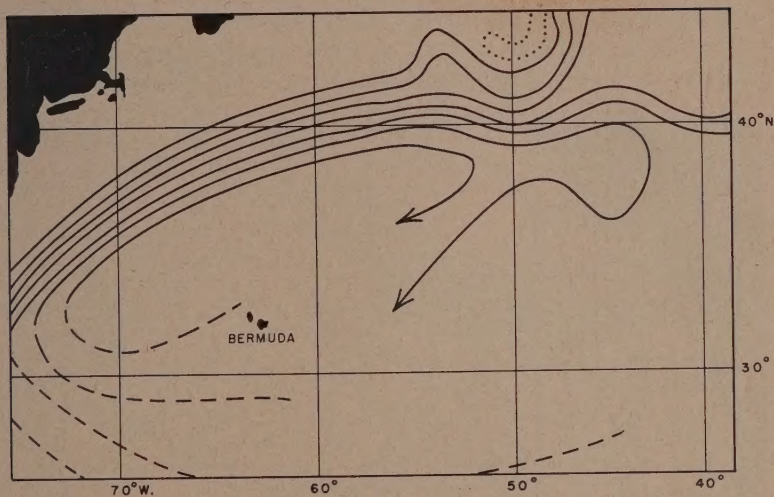


FIGURE 6. Portion of the Gulf Stream System, according to Iselin (1936).

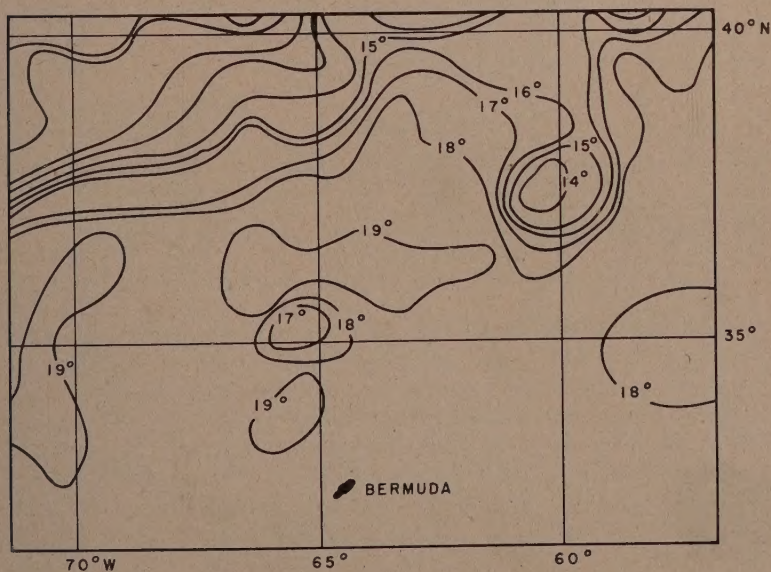


FIGURE 7. Temperature (°C.) at 200 meters, after Fuglister.

at a depth of 200 meters in the North Atlantic, and finally Moore (1952) has published a chart of water transparency in the area (Figure 8). Both of these suggest the presence of such an eddy in the

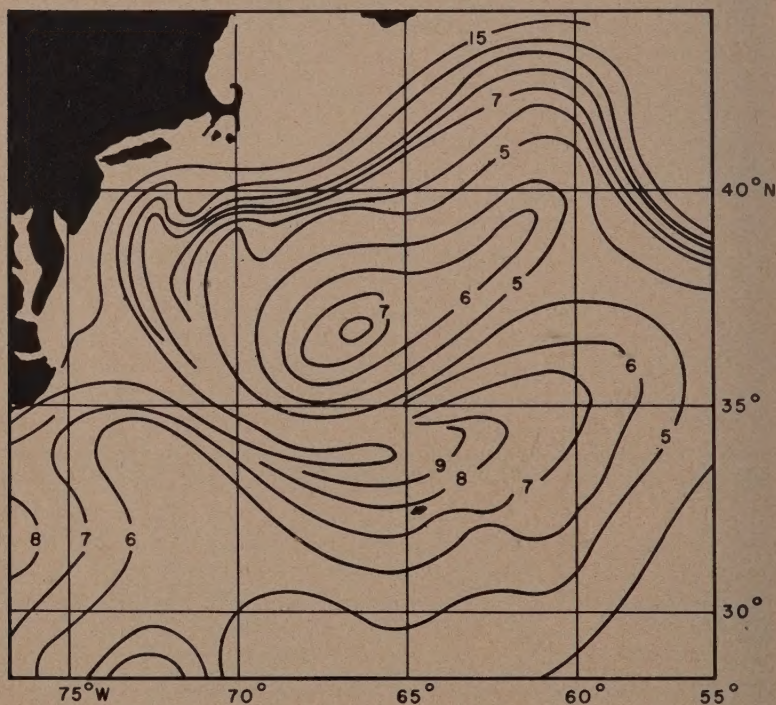


FIGURE 8. Extinction coefficients ($\times 100$), according to Moore (1952).

neighborhood of Bermuda. One may assume that a comparatively slight seasonal shift might well bring summer and winter plankton populations from widely separated areas into the vicinity of Bermuda.

Hela (1954) has computed the resulting surface currents of every degree square and for the different seasons separately by means of the monthly current charts published by the U. S. Navy Hydrographic Office (H. O. Publ. 571, sheets 1 through 12). The winter and summer current conditions are given schematically in Figures 9 and 10. In the winter chart (Figure 9), the eddy pointed out by Iselin (Figure 6) can be seen distinctly. The shaded area has been copied from

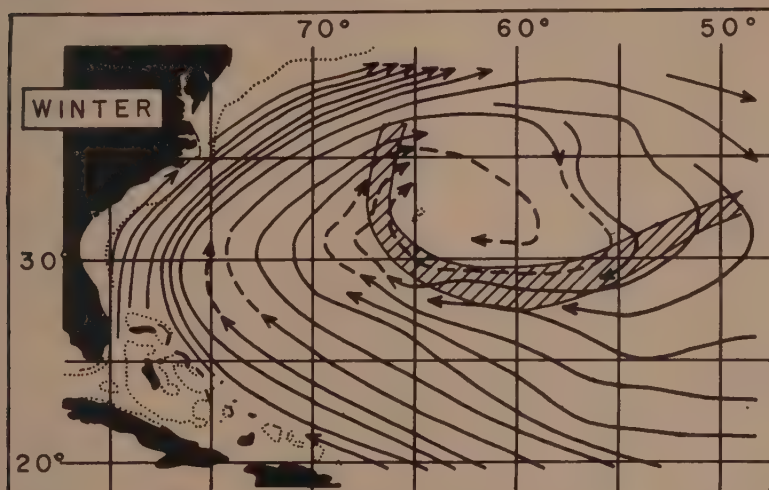


FIGURE 9. Winter current conditions with the "winter water" area (shaded) from Figure 5 included.

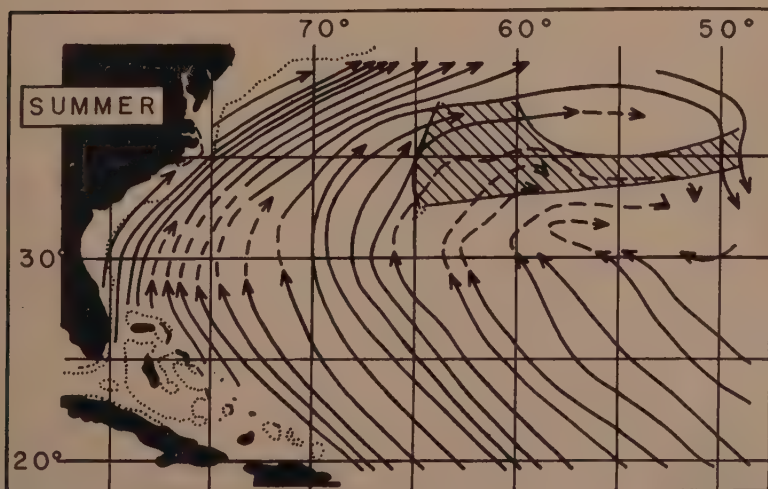


FIGURE 10. Summer current conditions with the "summer water" area (shaded) from Figure 5 included.

Figure 5 and corresponds to the "winter water" area south and west of Bermuda. In the summer chart (Figure 10), no indication whatsoever can be seen of the above eddy. In this case the shaded area has similarly been copied from Figure 5 and corresponds to the "summer water" area north and northeast of Bermuda.

The difference in the current system between winter and summer can be simply interpreted as follows. In winter the waters reaching Bermuda seem to come from the southeast and east roughly along the 30° north latitude parallel. These waters build the eastern and southern sections of an eddy of the Gulf Stream south of it, as indicated in Figure 9. Thus the "winter water" which is to be found south and southeast of Bermuda during the winter is nothing else but the south and westbound eddy of the Gulf Stream.

In summer the waters reaching Bermuda seem to come, directly from the south and southeast, from the North Equatorial Current. The mean direction of the surface currents (usually called Antilles Current) in the area seems to be roughly 300° in winter and 330° in summer. There are some indications, too, that in summer, in addition to the regular Antilles Current, another current branch exists with an approximate path from 20°N. and 60°W. to 30°N. and 67°W. Thus the "summer water" which is to be found west and southwest of Bermuda during the summer is just water coming directly from the North Equatorial Current.

The evidence from the geographical distribution of the plankton indicates the passage of waters of different origins around Bermuda in winter and summer. The above interpretation of the surface current systems is consistent with the indications from the plankton. The water, and its fauna, which passes Bermuda in winter has a more southerly origin than that which passes there in summer.

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THE PINEAL APPARATUS OF TUNAS AND RELATED SCOMBRID FISHES AS A POSSIBLE LIGHT RECEPTOR CONTROLLING PHOTOTACTIC MOVEMENTS¹

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ABSTRACT

A combination of closely related light transmitting structures dorsal to the brain of tunas and other scombrid fishes is described as the "pineal apparatus." Owing to the functional relationship apparently existing between this apparatus and the pineal area of the brain, and on the basis of the known correlation between light exposure of the pineal area and phototaxis in fishes, it is assumed, pending further confirmation, that the pineal apparatus may be a light receptor partially controlling phototactic movements.

INTRODUCTION

While dissecting a large specimen at Wedgeport, Nova Scotia, during the early part of October, 1952, it was discovered that the Bluefin tuna (*Thunnus thynnus*) possesses a median, translucent oval "window" in the skin at the interorbital region, leading to the brain and transmitting light, by means of a tube through a foramen in the skull. On the basis of recent investigations on the correlation between light exposure of the pineal area of the brain and phototaxis in fishes (Breder and Rasquin, 1950), this discovery is considered as a clue to the possible effect of light as a factor in the control of certain movements in tunas and other scombrid fishes. Although the structures herein described were first detected in the bluefin tuna, they were subsequently found to occur also in all of the other species of *Thunnus* (including *Germo*, *Parathunnus* and *Neothunnus*) and certain related genera (*Auxis*, *Katsuwonus*, *Euthynnus*, *Sarda*).

The preliminary work, involving mostly gross dissection, was conducted on the above mentioned specimen at Wedgeport during an expedition conducted by the writer in connection with the "Western North Atlantic Bluefin Tuna Cooperative Research Program" (Rivas, 1952). A brief, advance notice of the present study appeared in the

¹Contribution No. 114 from the Marine Laboratory, University of Miami.

Annual Report of the project for the year 1952. Mr. Charles F. Johnson, sponsor of the bluefin tuna research program, provided transportation to, and working facilities at Wedgeport and took active part in the expedition. His kind cooperation is gratefully acknowledged here. Thanks are also due to Dr. Charles M. Breder, Jr., and Miss Priscilla Rasquin, of the American Museum of Natural History for reading the manuscript critically and offering valuable suggestions. In cases where these have not been followed, the author assumes complete responsibility. Donald de Sylva of the University of Miami Department of Zoology assisted with the collection of fresh material and some of the dissections.

In addition to the specimen examined at Wedgeport, the present study is based on fresh and preserved material of several species of scombrid fishes obtained in Massachusetts, Florida, Bahamas, Cuba, Hawaii, and the Gulf of Panama. Through the facilities of the Lerner Marine Laboratory of the American Museum of Natural History, additional study material was obtained from large specimens of bluefin tuna, at Bimini, Bahamas, during June, 1953.

ANATOMICAL DESCRIPTION

Careful examination of the black dorsal surface of the head of a tuna (*Thunnus*), reveals the presence of a median, broadly elliptical, depigmented patch, about the size of the pupil, on the interorbital region (Fig. 1). When the interorbital skin is removed, it is easily detached from the muscle but remains firmly attached at the area where the patch occurs. At this point, the loose skin may be folded back and found to be considerably thickened (dermally), translucent, and attached to the cartilage and bone forming the median, longitudinal frontal ridge of the skull (Fig. 5; A). Kishinouye (1923: 313, 351) refers to this part of the head as "... a ligament connecting the skin to the skull", without any reference to its possible function. Upon complete removal of the skin, the depigmented patch is found to form a translucent, more or less oval window sharply contrasting with the heavily pigmented, opaque surrounding area (Fig. 2). The external plane of the window forms an angle of about 22 to 25 degrees with the body axis of the fish.

Owing to the functional relationship apparently existing between this structure and the pineal area of the brain, as subsequently discussed, the translucent patch will henceforth be referred to as the "pineal window".

No mention or description of this structure has been found in the literature, but a study of fresh and preserved specimens has revealed that in addition to the genus *Thunnus*, a pineal window is also present in *Scomber*, *Auxis*, *Katsuwonus*, *Euthynnus*, *Sarda*, *Scomberomorus* and *Acanthocybium*. A pineal window may also occur in other genera of Scombridae (material not available at present to the writer); and preliminary inspection indicates that a similar, but less developed structure is also present in the sailfishes and marlins (Istiophoridae).

The translucent dermal tissues overlying the pineal area of certain fishes studied by Breder and Rasquin (1947, 1950) are more or less evenly depigmented throughout the dorsal surface of the head, or do not form as specialized a dermal window as in the tunas. In these fishes, which belong mostly to nonacanthopterygian groups (Clupeidae, Dussumieriidae, Characidae, Atherinidae, etc.) far removed from the Scombridae, admission of light into the pineal area is effected through translucent skin and bone, or through connective tissue occupying a frontoparietal fontanelle.

A study of the median frontal ridge of the skull of scombrids at the area of attachment of the pineal window, reveals a swelling roofed over by translucent cartilaginous tissue, and located immediately in front of the supraoccipital crest (Fig. 5; B). The flat roof of the swelling coincides in outline and position with the pineal window, whose inner surface lies immediately above.

A sagittal section of the head shows that internally, the frontal swelling forms the closed end of a straight tube leading to the pineal area of the brain, through the adipose tissue filling the anterodorsal part of the brain cavity (Fig. 5; C, D). Throughout the swelling, the tube is more or less elliptical in cross-section, but it becomes cylindrical upon entering the adipose tissue. The axis of the tube is inclined forward and coincident with the center of the cartilaginous roof which in turn is coincident with the center of the pineal window. The axis of the tube forms an angle of about 35 to 38 degrees with the body axis, about 60 degrees with the external planes of the cartilaginous roof and the pineal window, and about 26 degrees with the axis of the pineal window. The external planes of the cartilaginous roof and the pineal window are more or less parallel. The internal surface of the roof or "ceiling" of the tube, is strongly concave except at a small area of the center (apex) where it is flat, parallel with the outer surface and very thin in cross-section (Fig. 5; B). Looking through the tube into the brain with the cartilaginous roof removed, only the pineal

area is visible immediately beneath the meninges which form part of the bottom of the tube. The tube is filled with a jelly-like fluid, comparable in viscosity and general appearance with the vitreous humor of the eye.

The frontal swelling may be considered as an anterior, domelike, upward extension of the brain cavity and will henceforth be referred to as the "pineal dome" for the same reasons already ascribed to the pineal window. The tube, whose distal end is formed by the pineal dome, will be referred to as the "pineal tube."

A pineal dome has been found in all of the scombrid genera already mentioned which also possess a pineal window, with the exception of *Scomber* and *Scomberomorus*. Allis (1903: 73; pl. 4), however, has described in *Scomber* a more simplified structure obviously equivalent to the pineal dome of *Thunnus* and related genera. He refers to it as the "postepiphysial interspace of cartilage".

Although the pineal dome is roofed over with cartilage in fresh specimens, its study in defleshed, dry skulls brings out the significance of the median, frontal foramen typically occurring in *Thunnus* and related genera.

An inspection of published figures (Kishinouye, 1923, pls. 28, 29, 32, 33; Gregory, 1933: 313, Fig. 192A; Godsil and Byers, 1944: 41, Fig. 17, 67, Fig. 33) or actual examination of dry skulls, reveals the presence in *Thunnus*, as well as in other related genera (*Auxis*, *Katsuwonus*, *Euthynnus*, *Sarda*), of a conspicuous, more or less oblong foramen leading into the brain cavity and located at the frontal ridge immediately anterior to the supraoccipital crest (Fig. 3). This opening (henceforth referred to as the "pineal foramen") is formed by the outcurving of the posterior, upper edges of the frontals anterior to the sutures connecting them with the supraoccipital. The edges approximate after forming the foramen and give rise to the grooved ridge extending to, and joining the dermethmoid. In other genera (*Scomber*, *Scomberomorus*), no well defined foramen occurs and the frontal ridge is continuous from the supraoccipital. Kishinouye (1923: 313) refers to the frontal foramen as a "slit" and states that "in the Plecostei it is large and always conspicuous". Recently Nakamura (1952: 4) briefly describes this opening as "a conspicuous foramen" formed by the "... posterior edges of the frontals ... not fused together over the alisphenoids ..."

Internally, the foramen leads directly into an anterior, upward extension of the cranial cavity (pineal dome) whose anterior wall is

formed by the internal wings of the frontals, joining medially by suture (Figs. 3, 4 and 5; E).

It is evident from the study and comparison of fresh heads and dry skulls, that the roof of the pineal dome is actually an inverted, cartilaginous cup with its bottom occupying and closing the frontal foramen and its walls lining those of the dome (Fig. 5; B). Internally, the cup abuts with the supraoccipital and alisphenoid posteriorly and rests against the joined, internal wings of the frontals anteriorly (Fig. 5; E, F, G).

Without attempting to draw any functional conclusions at this point, it may be indicated however, that the pineal window, pineal dome, and pineal tube, form a combination of closely associated organs (henceforth referred to as the "pineal apparatus"), significantly arranged and modified so as to permit the passage of light into the pineal area. When the pineal apparatus is observed by transmitted light from inside, the area of translucency appears to be much smaller than the window itself, and concentrated at the center. This is obviously due to the cross-sectional shape of the cartilaginous roof of the pineal dome, as already described (p. 170, and Fig. 5; B). The resulting beam of light is coincidental with the axis of the pineal tube, and a collimating effect is thus obtained. Preliminary tests with a photometer show that the pineal apparatus allows the passage of about 25 percent of the light falling on the pineal window of large bluefin tuna (about 500 lbs., 2350 mm).

The pineal apparatus is essentially the same in all the species examined which possess it with small dimensional variations between genera. There is no ontogenetic, structural variation (from the juvenile on) within species.

Compared with the structures described by Breder and Rasquin (1947, 1950), the pineal apparatus appears to be much more complex and specialized, as may be expected from the more advanced phylogenetic position of the tunas. In the fishes studied by these authors (*Sardinella*, *Jenkinsia*, *Anoptichthys*, *Atherina*, *Sphyræna*, etc.) light is admitted into the pineal area through translucent skin and bone, or by means of a longitudinal, rather wide, frontoparietal fontanelle immediately above the brain, most of which is dorsally exposed. There is no specialized pineal window, no pineal dome, no pineal foramen, and no pineal tube, and therefore light does not appear to be directionally transmitted.

Breder and Rasquin (1950: 2) have pointed out that "... there

is a strong semblance of phylogeny inherent . . . " in the degree of exposure to light of the pineal area and that there is " . . . a clear reduction of pineal influence as one reaches the spiny-rayed fishes". This is correlated with the increase in complexity of the structures dorsal to the brain, including thickness and opacity of the skin and bone, reduction or absence of a fontanelle, occurrence of muscle and deeper location of the brain, resulting in complete absence of light penetration.

In connection with the functional properties hypothesized for the pineal apparatus and to be discussed in the next section, it is significant that in typical, spiny-rayed fishes like the tunas (well above groups in which pineal influence does not apparently exist), a specialization for light transmission has occurred along with the increase in complexity of the dorsal part of the cranium. Despite the deep location of the brain (immediately above the body axis) and the considerable thickness and opacity of the bone, muscle, and skin overlying it, which otherwise would not at all allow the passage of light, a pineal apparatus has been evolved. It is also significant that in addition to the obvious, light transmitting properties of the pineal apparatus, the pineal tube directs light only into the pineal area and to no other part of the brain.

PHYSIOLOGICAL AND BEHAVIORAL INFERENCES

The functional characteristics of the pineal area of the brain, in relation with phototaxis in fishes, have been investigated by various workers, but mostly on a speculative basis. Little experimental work has been conducted, and many observational deductions obtained in the field remain unconfirmed. Von Frisch (1911a, 1911b), has shown that the pineal area of the brain of fishes is light sensitive and according to Breder and Rasquin (1950), this was later confirmed by Scharrer in 1927. More recently, Breder and Rasquin (1947, 1950), have investigated the problem experimentally and demonstrated the existence of a definite correlation between certain morphological conditions affecting the pineal area and the reactions of fishes to light. Their studies show that in various species, the degree of exposure to light of the pineal area, has a distinct influence on phototaxis. According to these findings, fishes in which the translucency of the tissues overlying the pineal area, permits light to enter, are, with very few exceptions, light-positive (*Jenkinsia*, *Sardinella*, *Atherina*, etc.). On the other hand, those in which the tissues are too opaque to allow any penetration of light, are mostly light-negative (*Ameiurus*, *Hae-*

mulon, *Thalassoma*). An intermediate or changeable condition (by chromatophore control) in the translucency of the tissues, results in an also intermediate or changeable phototactic response (*Sphyræna*, *Strongylura*, *Synodus*).

The fishes with permanently or controlled, light-exposed pineal areas used in the studies referred to above, are all said to possess a pineal organ (epiphysis), and Breder and Rasquin (1950: 1) state that this structure is "... evidently present ..." in all recent teleosts. However, a study of the brain of *Thunnus* and the related genera considered in the present work, fails to reveal the presence of a pineal organ which is apparently absent or greatly reduced, as already pointed out by Conrad (1937: 3).

The absence of a visible pineal organ in tunas cannot be accepted as evidence that the pineal area of these fishes does not react to light, especially since von Frisch (1911), was able to demonstrate that light sensitivity was not entirely eliminated by removal of the pineal organ. Furthermore, the presence of the well developed pineal apparatus described in this study correlated with the recently demonstrated existence of positive phototaxis in tunas (Hsiao, 1952), strongly suggests that these fishes must react to light, and that the resulting phototactic movements could be at least partly induced by the pineal area of the brain through the pineal apparatus.

The existence of phototaxis in tunas has been recently established experimentally by Hsiao (1952) on the basis of controlled, artificial light. The species used in his studies were the Pacific yellowfin tuna ("*Neothunnus macropterus*") and the Pacific little tunny ("*Euthynnus yaito*"), and the conclusions reached were based solely on the visual organ. Hsiao's experiments were conducted at night on specimens held captive in a concrete tank, and involved submerged, horizontal beams, and light radiated in all directions from a submerged bulb. These experiments demonstrate a positive tropism to continuous, white light of a certain intensity (70 to 450 foot-candles), and according to the evidence presented in this study, these reactions may have been partially induced by the pineal apparatus rather than totally by the eyes. Breder and Rasquin (1947: 332) have shown that in certain fishes (*Astyanax*), removal of the optic cyst inhibits reactivity to light, but that when the cyst is allowed to remain intact, positive phototaxis shows correlation only with the degree of exposure of the pineal area.

As already described, the directional effect of the pineal apparatus

would only allow the passage of light coming from above. The correlation of these morphological conditions with illumination in the open sea is significant. Even with the sun at the horizon, refraction will cause the rays of light penetrating the water to bend at an angle of not more than fifty degrees with the vertical or about forty degrees with the horizontal. The axis of the pineal tube forms an angle of about 35 to 38 degrees with the body axis, which would seem to indicate that the pineal area is not fully affected by refracted, directional light. However, the inclination of the pineal window and the scattering effect caused by its translucency, allows the efficient transmission even of vertical rays, as shown by photometric tests conducted in the laboratory. The highest intensity of light reaching the pineal area is obtained with rays falling more or less perpendicular to the plane of the pineal window and forming an angle of about 20 to 30 degrees with the vertical. This would correspond to an altitude of the sun of about 45 to 60 degrees.

According to data on illumination obtained from Sverdrup, Johnson and Fleming (1946: 775, 776), the range of light intensity (70 to 450 foot-candles) to which tunas seem to react corresponds at noon, in the summer, to depths of about 90 to 140 meters in clearest ocean water, and 45 to 75 meters in average ocean water. It is interesting to note that according to Kishinouye (1923: 393), the Pacific species of *Thunnus* are mostly found in depths between 20 and 100 meters and seldom or never in depths of more than 130 meters. In the clear waters of the Gulf Stream off Havana, Cuba, large individuals of bluefin tuna are captured by the long-line swordfish and marlin fishermen, nearly always in depths between 100 and 200 meters. The approximate coincidence of these figures suggests an interesting line for future studies.

CONCLUSIONS

The evidence presented in this study suggests that tunas, and other related scombrid fishes, react to light by means of a pineal apparatus. In the open sea light may be one of the factors controlling their vertical movements. The correlation between sun altitudes, light intensities, direction of rays, water transparencies, depth, etc., and the behavior of tunas under natural and experimental conditions, remains to be worked out and no definite conclusions can be derived at present.

In order to verify the functional properties assumed for the pineal

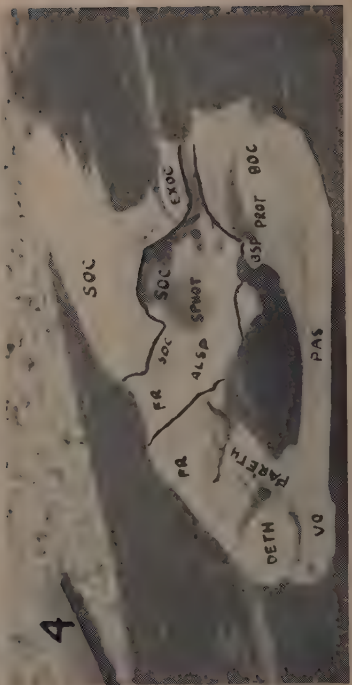
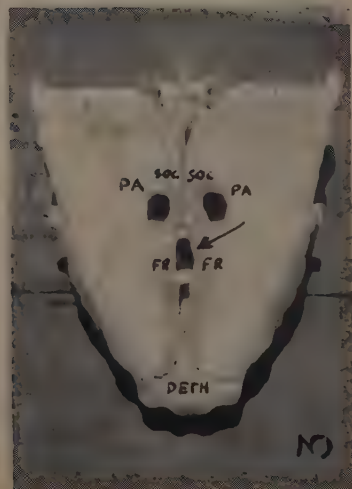


FIGURE 1. Laterodorsal view of head of young specimen of bluefin tuna (*Thunnus thynnus*), showing external appearance and location of pineal window. (Photograph courtesy of the Miami Daily News).

FIGURE 2. Interorbital patch of skin of large, adult specimen of bluefin tuna (*Thunnus thynnus*), photographed from the dorsal side against a bright sky, showing translucency and outline of pineal window. Note index finger of observer clearly silhouetted behind window. (Photographed by Donald P. deSylva).

FIGURE 3. Dorsal view of neurocranium of large, adult specimen of bluefin tuna (*Thunnus thynnus*), showing external appearance and location of pineal foramen. (Photographed by Donald P. deSylva).

FIGURE 4. Median sagittal section of neurocranium of large, adult specimen of bluefin tuna (*Thunnus thynnus*), showing internal appearance and location of brain cavity and its anterior upward extension associated with pineal structures. The indentation anterior to the supraoccipital crest indicates location of pineal foramen. (Photographed by Donald P. deSylva).

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FIGURE 5. Median sagittal section (except brain) of partially defleshed neurocranium of large, adult specimen of bluefin tuna (*Thunnus thynnus*), showing structure and location of pineal apparatus. A. Translucent, dermal tissue of pineal window. B. Translucent, cartilaginous roof of pineal dome. C. Pineal tube. D. Adipose tissue. E. Frontal. F. Supraoccipital. G. Alisphenoid. H. Axis of body. I. Proencephalon. J. Optic nerve. K. Optic lobe. L. Cerebellum. M. Hypoartium. See text for further explanation. (Semidiagrammatic drawing by the author; one half natural size).

apparatus, and to confirm further the existence of a positive phototropism in tunas, additional evidence based on histological studies and experimentation is needed. The feasibility of keeping tunas in captivity for experimental purposes has been recently demonstrated by Tester (1952), and experiments patterned after those of Breder and Rasquin (1947) are proposed towards the solution of this problem. The arguments presented here with regard to the probable function of the pineal apparatus are based on the assumption that the structure herein referred to as the pineal area, is actually photoreceptive in nature. It is felt justified to present the evidence in its present form, in the hope that it will stimulate further work on the subject. The histological examination needed to confirm these results is already planned.

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THE HYDROGRAPHY OF PAMLICO SOUND^{1,2}

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ABSTRACT

The horizontal distribution of salinity in Pamlico Sound is influenced by wind and long-term runoff. Vertical salinity gradients are minimal (<0.7 ‰/20 feet) in the main body of the sound, intermediate (>12 ‰/20 feet) in the river mouths and maximal (>14 ‰/9 feet) in the northern part of Core Sound. Water temperature closely follows air temperature with practically no stratification. Currents in the sound resulting from wind friction reach velocities of 69 cm./sec. Currents resulting from runoff are calculated to be of the order of 0.5 cm./sec. Tidal exchange in the inlets amounts to about $220 \times 10^6 \text{ m}^3$ per tide. This amount, equivalent to 8 times the average river flow, would produce a rise and fall over the whole sound of 5 cm. Estimates of wind "setup" at the northern end of Pamlico Sound are made.

INTRODUCTION

Pamlico Sound, a broad shallow sheet of water bathing the shores of the northeastern counties of North Carolina, is the largest of the embayments formed behind barrier beaches along the Atlantic Coast of the United States. Compared to other coastal embayments it is relatively shallow. It has a large watershed but the annual fresh-water acquisition is less than the volume of the sound. Access to the sea is had through small unstable inlets. The astronomical tidal effect in the sound is immeasurable. Wind tides are large. The tidal prism occasioned by the semidiurnal tidal rise and fall outside the inlets is about eight times the average one-half daily river flow. Currents in the inlets are strong whereas those in the body of the sound are weak, dependent upon the wind. Vertical gradients in temperature and salinity are virtually lacking.

Studies of the hydrography of these waters have been made during the past 65 years, chiefly in conjunction with oyster culture investigations. Winslow (1886, 1889) made a number of salinity observations.

¹Contribution Number 37 from the Institute of Fisheries Research, University of North Carolina.

²Contribution Number 547 from the Woods Hole Oceanographic Institution.

His reports do not include a tabulation of the data, but several general statements were made regarding the salinity distribution and the effects of the wind on the sound waters. Grave (1904) and Coker

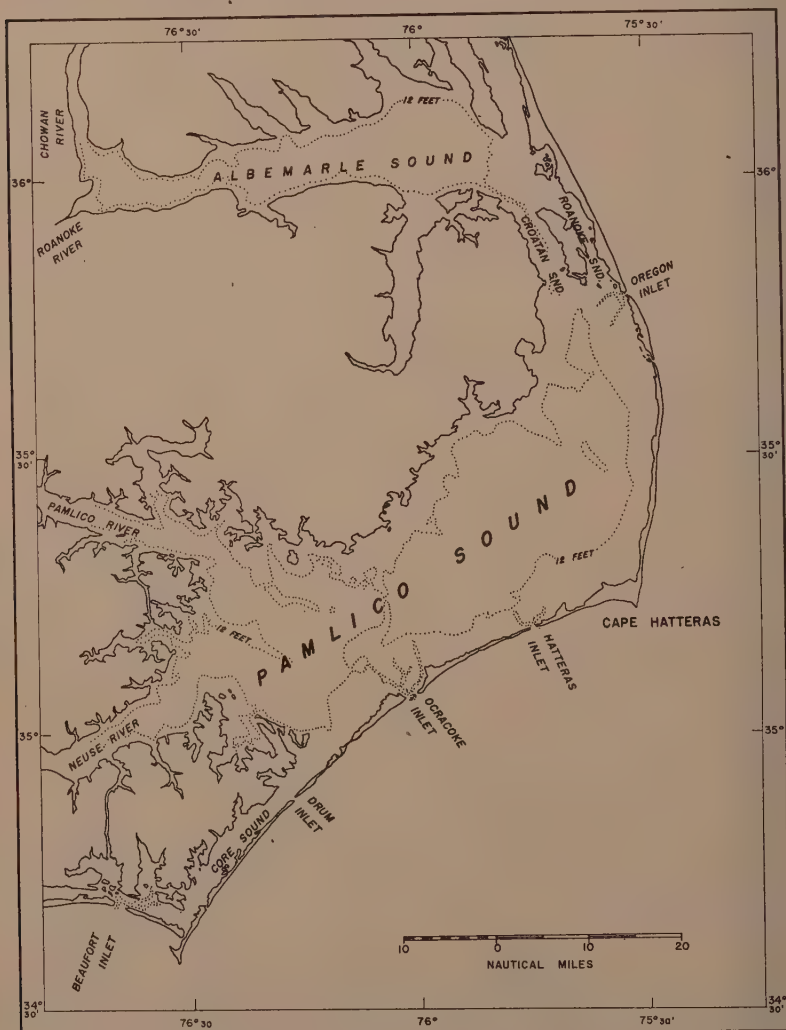


FIGURE 1. Orientation chart of Pamlico Sound and tributary waters.

(1907) made some hydrographic observations in the sound, but these are so limited that they added little to the previous knowledge. Seiwel made monthly observations of temperature and salinity from November 1926 to September 1927, covering a "dense network of stations" in the Pamlico Sound area. His data have not been published, but his typewritten report and a number of graphs and charts based on his data have been made available.

The Beach Erosion Board (1935, 1948) has made certain current measurements from time to time in connection with attempts to stabilize the inlets.

The present discussion is based on data obtained since June 1948, when a hydrographic program was initiated at the University of North Carolina, Institute of Fisheries Research. These data permit a discussion of the salinity and temperature in various parts of Pamlico Sound, together with seasonal and yearly variations, as well as certain aspects of the tides and currents which are peculiar to it.

PHYSIOGRAPHY

Pamlico Sound (Fig. 1), a drowned river valley of the submerged coastal plain, is bordered by the mainland and its tributary rivers on the western side and by the emergent outer banks with their three inlets: Oregon, Hatteras, and Ocracoke Inlet³, on the eastern side.

At its northern end it connects with Albemarle Sound via Croatan and Roanoke Sounds, which are separated by Roanoke Island. At the southern end it is continuous with Core Sound.

Pamlico Sound is approximately 60 miles long and 15 to 20 miles wide, being narrowest at the northern end (9 miles) and widest opposite Hatteras Island (26 miles). The maximum depth of the main body of the sound is about 22 feet although, because of the extensive shoals around the margin and projecting into the sound, the mean depth is probably not more than 15 feet. The sounds adjoining Pamlico Sound are also shallow, Albemarle Sound being the deepest (15 to 20 feet) and Core Sound the shallowest (average 3 to 4 feet).

The area and volume of these waters are estimated to be as follows:

	Area x 10 ⁸ m ²	Volume x 10 ⁸ m ³
Albemarle Sound	18.2	65.4
Croatan Sound	1.2	3.4
Roanoke Sound	0.96	1.5
Pamlico Sound	43.5	166.0
Core Sound	2.4	2.9
Total	66.3	239.2

³Other inlets have been reported previously but have since sanded up (Drane, 1923, and Beach Erosion Board, 1948).

Two large river systems, the Neuse and the Tar-Pamlico, discharge directly into Pamlico Sound. These rivers originate in the north-central Piedmont section of the state, but over two-thirds of the 7,500 square mile combined drainage basin lies in the lower and flatter coastal plain region. Pamlico Sound also receives indirectly the discharge from the Chowan and Roanoke Rivers, the latter having its origin in the Allegheny Mountains of Virginia. These two rivers, draining an area of about 7,000 square miles, empty into the western end of Albemarle Sound which in turn empties into Roanoke and Croatan Sounds. The latter sounds join Pamlico Sound in the vicinity of Oregon Inlet.

In addition to the four river systems mentioned there are many short, wide streams draining the extensive low, swampy areas, characteristic of the North Carolina coast, which contribute to the water supply of the Pamlico Sound complex. The entire drainage area of the sound, including that of the large river systems, is estimated to be in the neighborhood of 20,000 square miles.

Except for Oregon, Hatteras, and Ocracoke Inlets, inlets are an impermanent feature of the outer banks. Even these inlets change in size and position. Shoals have formed both inside and outside the inlets. Those inside are extensive, shallow and cut by narrow, tortuous, continually changing channels. Only small craft piloted with local knowledge can safely navigate their waters.

SALINITY

At the beginning of the present study, 36 stations were established in the sound and its tributary waters. The stations were not uniformly distributed throughout the sound but were more numerous in the western area where the oyster industry is concentrated. At each station, surface and bottom temperatures and salinities were recorded. While this method yielded more information than was previously available, coverage of the area seemed inadequate. The large distances involved and the notoriously bad weather of the area prevented regular observations at some of the stations. In January 1951, on the basis of the findings during the earlier two and one-half year period, the sampling method was changed. It had been found earlier that differences in temperature and salinity between surface and bottom were so small as to be of little significance, at least insofar as the needs of the program were concerned. During 1951 and continuing through the spring of 1953, transects were made at various places across the sound taking readings only at the surface at approximately 1.6 mile

intervals. The latter method permitted coverage of a greater portion of the sound and a much larger number of observations.

Horizontal Distribution. Large fluctuations in salinity, dependent on runoff, occur in those parts of the sound adjacent to sources of fresh water. Large gradients in salinity occur near the inlets, where variations in the maximum salinity are dependent on the stage of the tide. Salinity fluctuations are least in the central body of the sound and are dependent on the winds and the long-term cycles of runoff.

In the southwestern part of the sound there is an east-west salinity gradient, the lowest salinities (9.3-19.2 ‰) being naturally found at the mouths of the Neuse and Pamlico Rivers and the highest salinities (up to 35 ‰) occurring at Ocracoke Inlet. In the northern part of the sound a north-south salinity gradient occurs with lower salinities again nearer the source of fresh water, Albemarle Sound.

Except for the net seaward flow required for the eventual discharge of runoff waters, the wind is the dominant force in determining the salinity distribution in the central part of the sound. Figure 2, based on data collected 18-22 April, 1950, exhibits the salinity distribution when there is no appreciable wind. The lowest salinities (15 ‰) are found at the western and northern ends of the sound; the highest salinities (20 ‰) in the north-central area and intermediate salinities in the west-central area.

Northerly winds cause the fresh waters from Albemarle Sound to penetrate farther into Pamlico Sound than is normal. As a result, the north-central part of the sound becomes less saline, as shown in Figure 3, based on data for 25-27 April, 1951.

Southerly winds, particularly those from the southwest have the opposite effect. The saltier waters from the vicinity of the inlets move in a northeasterly direction inside the outer banks, giving rise to a northwest-southeast salinity gradient in both the west-central and north-central sections of the sounds (Figure 4, based on data of 22-25 May, 1951).

Strong southwest winds occasionally move enough water northward to raise the sound water level above that of Oregon Inlet at high tide. During such periods there is a continuous ebb current through the inlet. Fishermen working around the inlet report that such ebb currents may last for two or three days during "sou'westers." Such an ebb current prevailed on 23 April, 1950, during the series of inlet studies reported below. The water which flowed out through Oregon Inlet during the entire period of observation was warmer and more saline

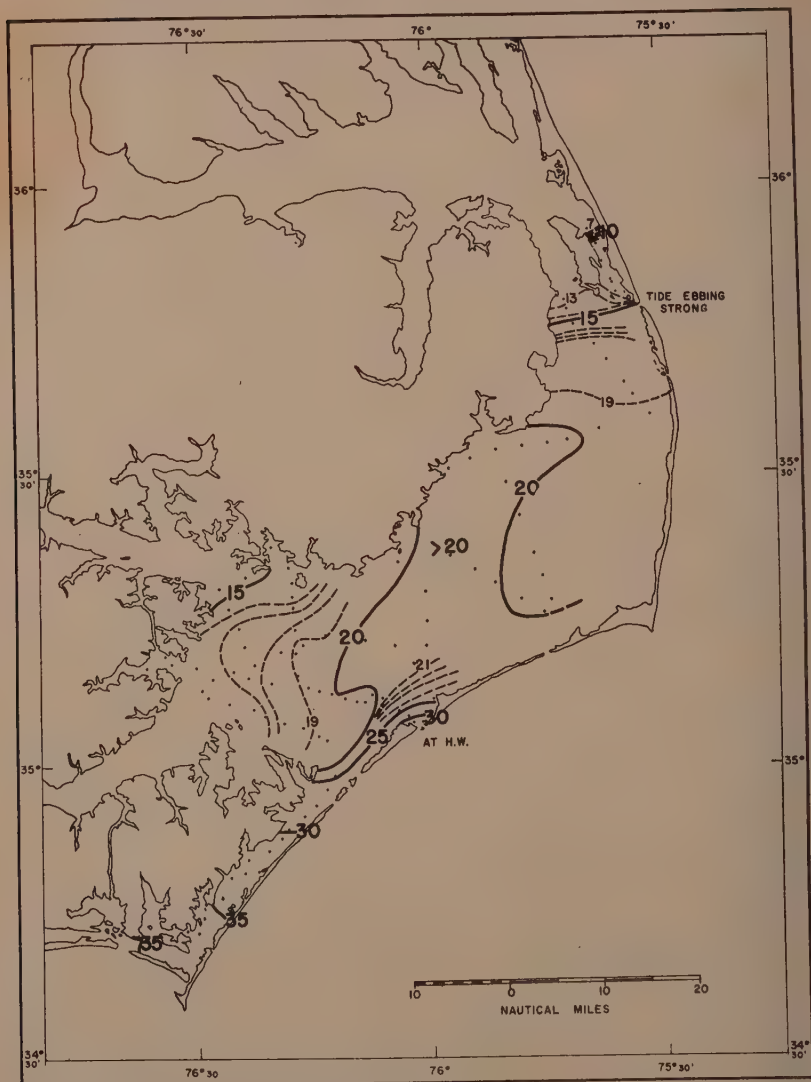


FIGURE 2. Surface salinity distribution in Pamlico Sound following a period having no appreciable winds. Based on data taken 18 - 22 April 1950.

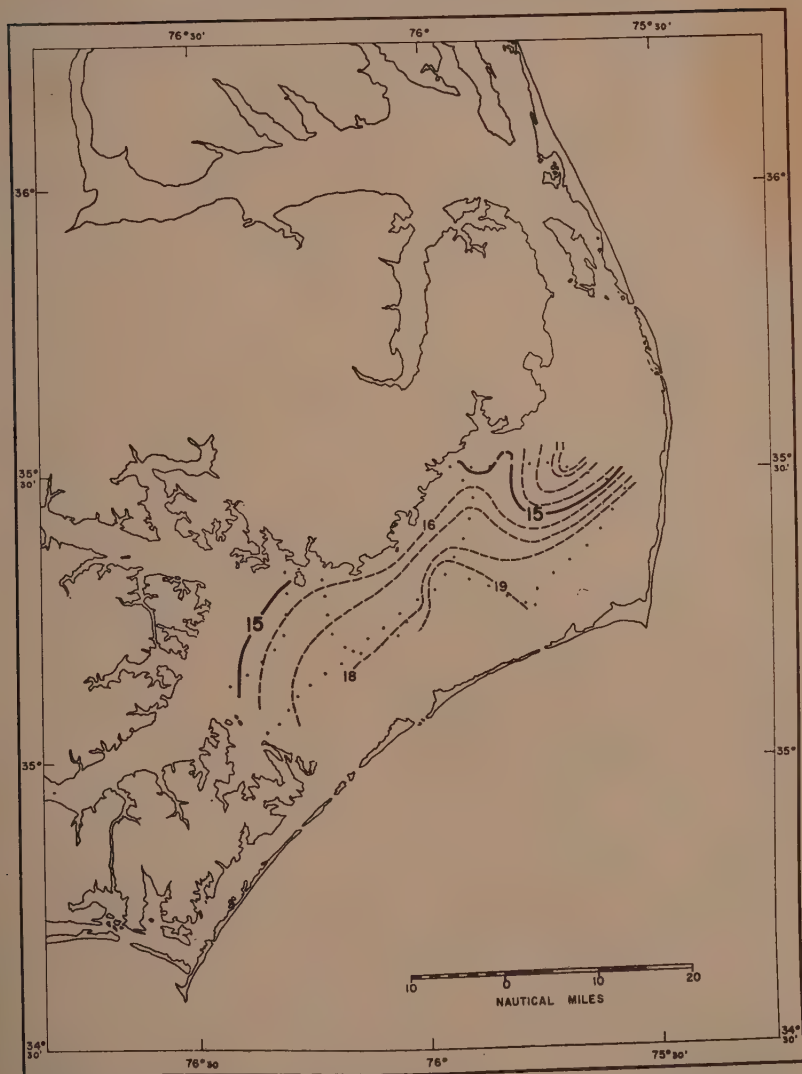


FIGURE 3. Surface salinity distribution in Pamlico Sound following strong northeasterly winds, showing penetration of fresher waters from Albermarle Sound into north-central Pamlico Sound. Based on data taken 25-27 April 1951.

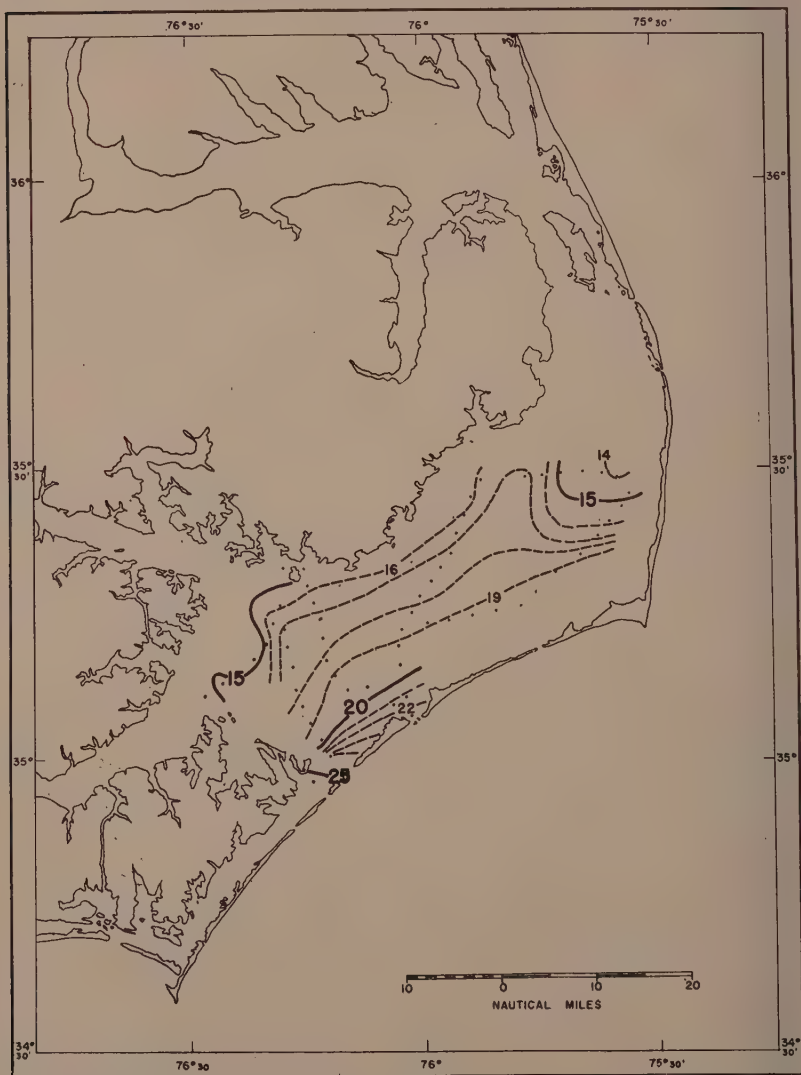


FIGURE 4. Surface salinity distribution in Pamlico Sound following southwesterly winds. Based on data taken 22 - 25 May 1951. Note that the fresher water shown in Figure 3 still persists.

than that found in the immediate vicinity on the previous two days. We believe that most of this water came from the shoals immediately to the south of the inlet. The strong southwest wind on this day could have backed the water of salinity less than 18 ‰ (see Figure 2) into Croatan Sound making this possible. On the following day, 24 April, the temperature and salinity data taken in the sound showed that ocean water had moved in through Hatteras Inlet and had continued northward just inside the outer banks. The waters on the shoals inside the barrier beach between Hatteras and Oregon Inlets contained 12 ‰ more salt than the open sound waters only a short distance away.

The effects of wind were observed by Winslow (1889), who reported that "Easterly winds will cause high water and high densities. Westerly winds will cause low water and low densities. Southerly winds will cause low water and low densities in the southern part of Pamlico Sound [*sic*] and high densities in the northern part. Northerly winds will have an exactly opposite effect in each locality." These general observations agree with the results of the present work except for the effect of southerly winds on salinity distribution as discussed above and shown in Figure 4. Winslow (*op. cit.*) in his discussion of winds also reported a relationship between Pamlico and Core Sounds which does not seem to be the case considering the present data. He writes, "Anomalous as it may seem, in Core Sound, its general direction being N. E. and S. W., a northeast gale will cause high water and high densities and a southwest gale the reverse—showing that the real outlet of that Sound is into Pamlico and not Beaufort Inlet, as would be supposed." The present study has revealed no such effect of winds on salinity in Core Sound. Salinities in Core Sound are always higher than in the adjacent part of Pamlico Sound. The effect of northerly winds is exactly opposite that reported by Winslow, in that the fresher Pamlico Sound water is "blown" into the upper part of Core Sound. On December 1, 1949, for example, the surface water at Harbor Island, about a mile south of a line separating the sounds, contained 14.4 ‰ salt compared with a salinity of 29.3 ‰ opposite Drum Inlet. The salinity at Hodges Reef in southern Pamlico Sound was 13.5 ‰. The bottom salinity at Harbor Island was 29.2 ‰, representing a salinity difference of 14.8 ‰ between surface and bottom, a distance of only nine feet. This condition can only be accounted for by a movement of Pamlico Sound water over the surface of the saltier Core Sound water. Vertical mixing did not occur because wave action in

the lee of Harbor Island was insufficient to mix waters of so great a difference in density.

There is a constant salinity gradient in Core Sound from northeast to southwest with higher salinities toward Beaufort Inlet (see Table 1). While Drum Inlet has some local influence, particularly on flood tide, and the rivers and bays entering Core Sound on the west may at times admit fresher water on an ebbing tide to lower the salinities at Bell's Island, the relatively high salinities and the salinity gradient in Core Sound force the conclusion that Beaufort Inlet rather than Pamlico Sound is the chief source of salt water for Core Sound.

It is remotely possible that the inlet situation in the late 1800's might account for the difference in conclusions as to the source of Core Sound water. Drum Inlet was then closed and Whalebone Inlet was open into the extreme southern end of Pamlico Sound. However, Whalebone Inlet was a small shallow inlet, as is Drum Inlet, and it seems doubtful that the presence or absence of either or both would significantly influence the gross hydrography of the area.

TABLE 1

SALINITIES IN PARTS PER THOUSAND IN SOUTHERN PAMLICO SOUND AND CORE SOUND STATIONS. FIGURES IN PARENTHESIS INDICATE DISTANCE IN MILES AND DIRECTION OF STATION POSITIONS IN REFERENCE TO POINT OF JUNCTION BETWEEN THE TWO SOUNDS.

Date	Hodges Reef (3N)	Harbor Island (1 SW)	Drum Inlet (7 SW)	Piney Point (15 SW)	Bell's Island (22 SW)	Wind Direction	Tide Stage
8/18/48	22.8	28.3	32.5	35.5	35.5	N	...
9/17/48	24.7	26.6	32.1	34.3	35.2	NE	Low
12/16/48	11.2	11.2	19.1	17.2	17.0	SW	Ebb
3/3/49	12.6	11.6	17.0	21.5	21.3	NE	Ebb
4/13/49	14.6	27.5	27.0	28.4	32.4	SSW	Ebb
6/1/49	20.1	17.6	22.1	25.8	27.5	NE	Fl.
6/27/49	14.8	24.2	31.5	30.9	31.2	SW	Fl.
9/28/49	19.5	20.1	24.4	25.1	28.0	N	Fl.
10/26/49	15.9	17.3	24.4	23.4	22.1	N	Fl.
12/1/49	13.5	14.4	29.3	32.7	33.3	NW	Ebb
9/15/50	14.6	21.8	26.7	22.7	29.3	NW	High
1/9/51	18.3	24.8	28.6	24.5	29.6	NE	Fl.
3/1/51	17.7	19.0	24.1	22.9	24.3	SW	Fl.
5/25/51	19.9	24.4	24.5	29.6	32.7	NW	Ebb
1/11/52	21.2	20.7	25.7	27.8	29.5	NW	Ebb
Average	17.4	20.6	25.9	26.8	28.6		

Vertical Distribution. As mentioned above, surface and bottom salinities were determined during the first two and one-half years of this study. The average difference between surface and bottom salinity in the sound was 0.66 ‰, indicating that there is a net "upstream movement" of more saline water along the bottom as described by other writers for many estuaries.

Pronounced stratification is occasionally found in the Neuse and Pamlico Rivers, where fresher waters flow on top of a more saline layer. In Neuse River, 10 miles above its entrance into the sound, on December 7, 1948, the surface salinity was 2.41 ‰; the bottom, at 24 feet, was 15.39 ‰—a difference of 12.98 ‰. On December 8, 1948 the difference between surface and bottom salinity in Pamlico River, about eight miles above its mouth, was 12.59 ‰. Such differences are not found in the main body of the sound because the size and shallowness of the sound facilitate thorough mixing by the almost incessant winds of the Cape Hatteras area.

Seasonal Variation. There is a seasonal salinity cycle in Pamlico Sound. The salinity is lowest during the period from February through May, after which there is a gradual salinity increase to the highest point in September or October (see Fig. 5). In general, although with some modification, this cycle is exhibited in all parts of the sound.

There are a number of factors influencing salinity; namely, rainfall, evaporation, river discharge, underground water sources, winds, and water exchange with the ocean.

The average rainfall for the area has been estimated from the charts in Linsley, Kohler and Paulhus (1949) as follows:

Period	Rainfall	Volume ⁴
December - February	0.30 m	20.0 x 10 ⁸ m ³
March - May	0.28	18.6
June - August	0.43	28.6
September - November	0.28	18.6
Average Annual	1.29 m	85.8 x 10 ⁸ m ³

The normal evaporation has also been estimated from the charts in Linsley, Kohler and Paulhus (1949) for the region as follows:

Period	Evaporation ⁵	Volume
May - October	0.81 m	53.8 x 10 ⁸ m ³
November - April	0.33	21.9
Average Annual	1.14 m	75.7 x 10 ⁸ m ³

⁴Rainfall x 66.3 x 10⁸m² (area of Pamlico Sound complex).

⁵From Class A land plans with a recommended coefficient of 0.7.

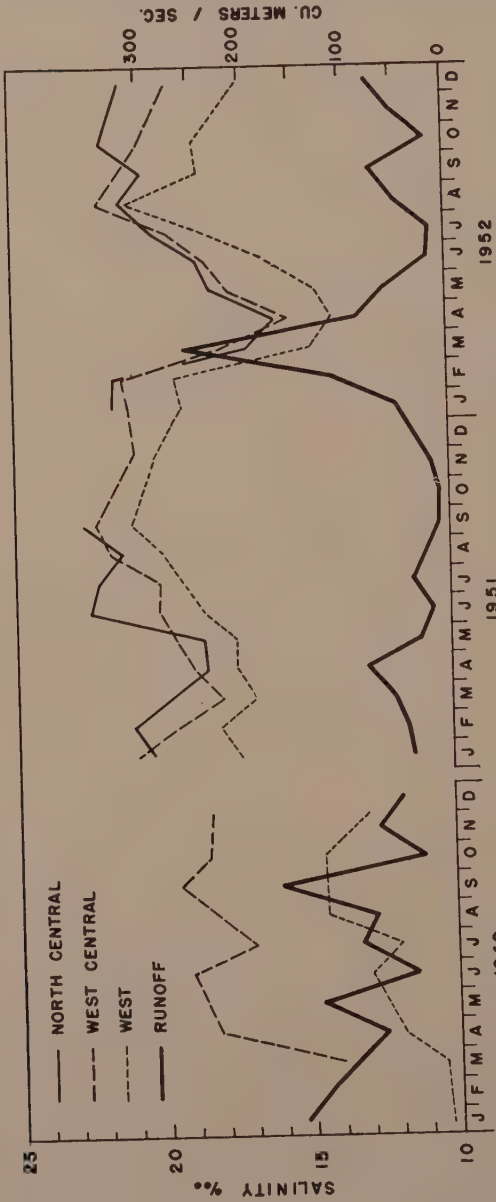


FIGURE 5: Graph of surface salinity of various parts of Pamlico Sound for 1949, 1951, and 1952, together with the runoff from the Neuse River, based on gage readings taken at Kinston, N. C., for the same years. All figures are monthly averages.

This average annual value of $75.7 \times 10^8 \text{m}^3$ is considerably less than that estimated by the Beach Erosion Board (1935); i.e., $114 \times 10^8 \text{m}^3$. Perhaps it is reasonable to assume that annually the rainfall into the sound and the evaporation from the sound nearly cancel out. It is also reasonable to assume from the data cited above that evaporation exceeds rainfall in the summer and the reverse in the winter.

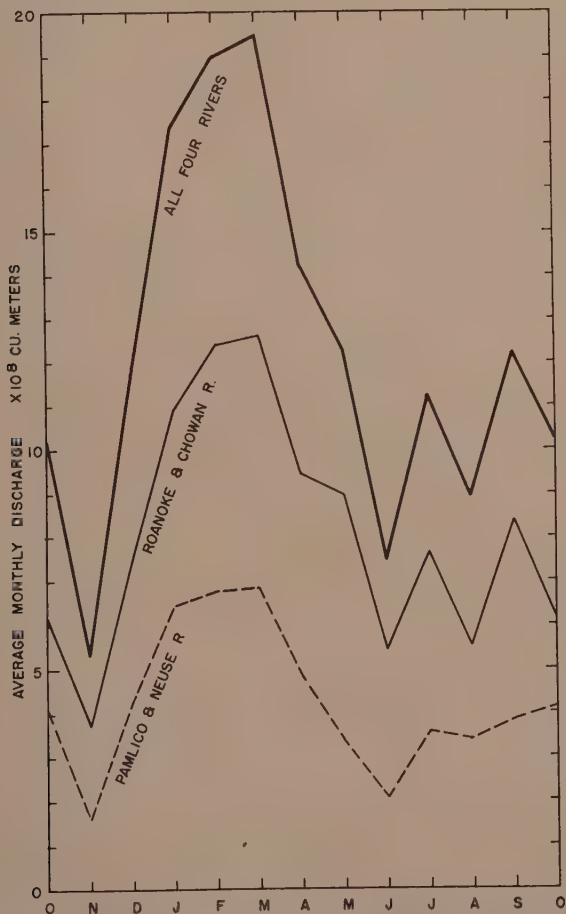


FIGURE 6. Mean monthly river discharge in the Pamlico Sound complex for the years 1941 - 1945.

Underground sources of fresh water for Pamlico Sound are unknown but probably exist (there are numerous artesian wells in Beaufort and Hyde Counties). However, Paulsen (1950) states that water levels in artesian wells are associated with rainfall, so the summer flow from such sources, although relatively small in volume, would be greater than at other seasons, and would counteract rather than intensify the seasonal cycle described above.

There is in Pamlico Sound an inverse relationship between salinity and river discharge or runoff. While there is some variation from year to year, the average runoff, Figure 6, is highest in the winter months and lowest in the summer months. The heavy runoff of the winter months depresses the salinity to a low point in March or April, Fig. 5, and coincident with the summer decrease in runoff, the salinity rises to a high point in late summer or early fall.

The annual discharge directly into Pamlico Sound, mostly from the Neuse and Pamlico Rivers, amounts to $78 \times 10^8 \text{ m}^3$ or only about 40%⁶ of the volume of the sound. If the discharge of the northern area—Albemarle Sound—is included, the total annual discharge into the entire sound complex is only slightly greater than the volume of Pamlico Sound. Hence, the discharge during any one month is so small as to produce little salinity change in the sound as a whole. The runoff during the first four months of the year, however, amounts to slightly more than 50% of the total runoff, and the accumulative effect of this winter discharge is a general decrease in salinity as shown above.

No information is available on the seasonal variation in the amount of salt water coming in through the inlets. This is undoubtedly related to the frequency, duration and direction of high winds. What few data are available on flow through the inlets are given in the section on Currents in the Inlets.

Yearly Variation. Year to year variations in rainfall produce fluctuations in runoff and these, in turn, are reflected by variations in the salinity of the sound⁷. During 1948 and 1949, for example, rainfall and runoff were considerably higher than the average for the period

⁶On the basis of the average river flow into and an estimate of the average volume of fresh water contained in Pamlico Sound, it takes approximately five months for a particle of fresh water to pass through.

⁷As Marshall (1951) points out, there is fairly close agreement between rainfall and runoff on a yearly basis; i.e., years during which the rainfall is high, runoff is also high, and vice versa. This relationship, however, does not exist on a monthly basis. Heavy rains in winter generally produce large river discharges, but heavy rains in summer seldom produce large discharges. This apparent anomaly is undoubtedly due to seasonal differences in soil condition, vegetative cover, transpiration, and evaporation.

1931 to 1949. Salinities throughout the sound were low during these two years. In 1951, rainfall and runoff were extremely low and the salinity of the sound was correspondingly higher. The salinity of the western part of the sound, for example, exceeded 20 ‰, whereas in 1949 it never exceeded 15‰. The heavy runoff in the spring of 1952 depressed the salinity of all portions of the sound, but during the summer the reduced runoff resulted in increased salinity. The salinity record of the various parts of the sound and its relationship to the runoff of the Neuse River⁸ is given for the years 1949, 1951, and 1952, in Figure 5. The salinities reported by Seiwel (Marshall, 1951) are high, being associated with a period of low runoff.

TEMPERATURE

Water temperature in Pamlico Sound shows a seasonal cycle closely related to air temperature. Temperatures are highest during late June, July, and August and are lowest during the winter months. Figure 7 shows the average monthly water temperature in Pamlico Sound during the period of study.

The relationship between air temperature and water temperature is shown in Figure 8. The points in the graph represent the average water temperature in the open sound plotted against the air temperature recorded at Hatteras. The air temperatures used in the graph represent the mean of the temperatures recorded on the day of observation and the previous day. This was done to allow for the lag in water temperature. The correlation coefficient between water temperature and air temperatures thus determined is .972.

There is no appreciable thermal stratification in the sound. Winds and wind-driven currents keep the water in nearly constant agitation and prevent stratification. Differences between observed surface and bottom temperature have never exceeded 2°C. Water flowing in the inlets is isothermal and during the winter months is frequently warmer than the sound water. The reverse is occasionally found in summer; i.e., the ocean waters are cooler than the sound waters. A temperature gradient may therefore be found in the vicinity of the inlets within the area of tidal influence. It is difficult to detect such a gradient in the open sound because of the diurnal variation within the sound. A change of 2 to 3°C. may occur at one station within a given day and

⁸Inasmuch as the runoff figures for all four rivers discharging into the Pamlico Sound complex show nearly identical monthly and seasonal variations, the figures for the Neuse River are considered satisfactory for showing the relationship between runoff and salinity.

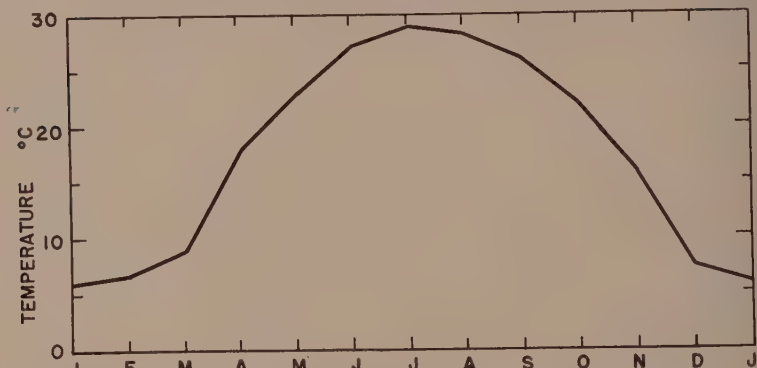


FIGURE 7. Mean monthly surface water temperature of Pamlico Sound.

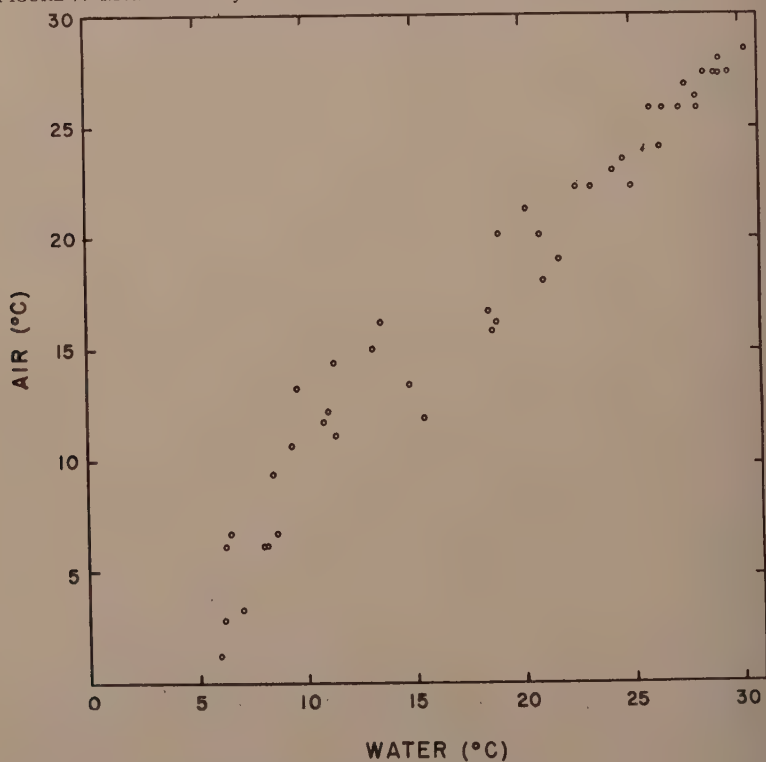


FIGURE 8. Relationship between surface water temperature in Pamlico Sound and air temperature at Hatteras.

as a general rule there is no greater difference between various parts of the sound on the same day.

CURRENTS IN PAMLICO SOUND

The currents in Pamlico Sound, which are relatively weak, depend mainly upon the direction and velocity of the wind, not upon tidal oscillation. Seiwel observed a maximum current of 69 cm./sec. in the mouth of the Neuse River during a squall. In his tabulation of currents during light winds the strongest currents observed were on the western side close to the mouth of the Neuse and Pamlico Rivers with drifts of 10 to 26. cm./sec. at the surface and 8 to 16 cm./sec. to depths of 15 feet. In the central part of the sound, surface currents of 1 to 9 cm./sec. were observed. He found no bottom current in the central part of the sound.

Winslow (1886) made a number of current measurements throughout Pamlico Sound and reported easterly and southeasterly currents in the southern part of the sound, seldom exceeding one-half knot (26 cm./sec.). The strongest current reported was three-fourths knots (38 cm./sec.) in a southwest direction; this occurred during a northeast gale which lasted for several days.

No current measurements were made in the sound during the present study.

However, we can calculate the order of magnitude of the mean current one might expect from the runoff of the Pamlico-Neuse River systems through a 20 mile section in the southwestern part of the sound. The average annual increment of fresh water is $78 \times 10^8 \text{ m}^3$ /year or about 200 cubic meters/sec. Let us assume this volume is augmented by an equivalent amount of salt water since the salinity is roughly half that of sea water. Let us further assume that the water is flowing seaward in only the upper half of the section, i.e., 2.6 m., with a return flow of more saline water beneath. Hence the area of the section is about $8 \times 10^4 \text{ m}^2$. Then the hydraulic current would amount to only 0.5 cm./sec. Even if our estimate were in error by a factor of 10 the runoff current would easily be over-powered by the currents due to wind friction.

CURRENTS IN THE INLETS

The only earlier current data in the inlets we have been able to find have been those published for Oregon Inlet in Beach Erosion Board (1935 and 1948) summarized as follows:

OREGON INLET

Date	Cross Section	Maximum Velocity		Maximum Rate of Flow		Total Flow	
		Flood	Ebb	Inflow	Outflow	Inflow	Outflow
		m/sec	m/sec	m ³ /sec	m ³ /sec	x10 ⁶ m ³	x10 ⁶ m ³
9 Sep '31	3650 m ²	0.76	0.70	3800	2520	58.6	46.0
31 Aug '32		.73	.79	3660	2900	52.5	49.8
11 Oct '32		.73	.98	3580	3600	42.8	70.4
24 Aug. '37	3970 m ²	1.13	1.01	5100	4020	78.0	68.7
14 Aug '39	5050 m ²	.85	1.16	4300	3990	46.5	87.9

NOTE: These observations were made when New Inlet was still open.

Current measurements were made at Oregon, Hatteras, and Ocracoke Inlets in April, 1950, with an Ekman Current Meter. Unfortunately, we succeeded in observing a full tidal cycle in Ocracoke Inlet only. The observations at other inlets covered a shorter period. However, they provide some useful information.

The current measurements at Oregon Inlet on 23 April were made at depths of 4 and 18 feet in the narrowest part of the channel where the sounding was 22 feet. They lasted over a period of 6-¾ hours during which time the current was continually ebbing, Figure 9. It appeared to have been ebbing for some time and to continue ebbing even longer. The current velocities at 4 feet varied from 88 cm./sec. to 138 cm./sec., averaging 115 cm./sec., while those at 18 feet varied from 62 cm./sec. to 129 cm./sec., averaging 88 cm./sec., yielding an average for the whole column of about 100 cm./sec. (2 kts.). Thus, about $47 \times 10^6 \text{ m}^3$ of water flowed out during the period of 6-¾ hours. This is assuming that the average velocity in the center of the channel was about 1/3 greater than the average for the whole cross section of 2,600 m². No doubt the strong southwest wind, force 4-5, built up a head of water at the northern end of the sound, causing the tide to begin ebbing before predicted high water and to continue ebbing after predicted low water. An estimate of the height of the head of water above mean sea level for the brief period of investigation is presented below.

Current measurements made in Hatteras Inlet on 25 April, at depths of 4 and 15 feet in the narrowest part of the channel where the sounding was 21 feet, were of nearly ten hours duration, Figure 10. The current was on the last half of the ebb when we commenced. The maximum ebb current observed was 94 cm./sec. The ebb continued nearly three hours after the predicted time of low water. The flood commenced about ¾ hour before predicted slack, flood begins

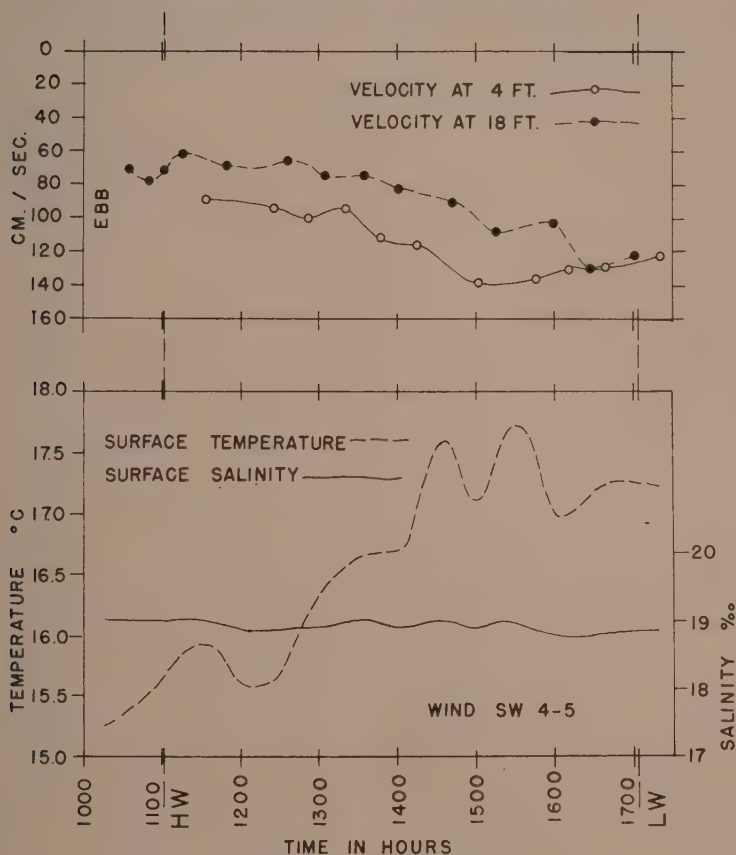


FIGURE 9. Observations at Oregon Inlet, 23 April 1950.

The flood current lasted nearly seven hours, with the maximum flood current being 91 cm./sec. and ended at predicted slack, ebb begins. The average current for the water column (there was little difference between the 4 and 15 foot measurements) was 46 cm./sec. (0.9 kts.). Thus, the total volume of flood, for the 6-¾ hours, assuming the average velocity in the center of the channel was about 1/3 greater than the average for the whole gorge of 7,700 m², was 65 x 10⁶m³. This volume of water is about equivalent to the volume in a rectangle 5 miles on a side over the shoals immediately inside the inlet.

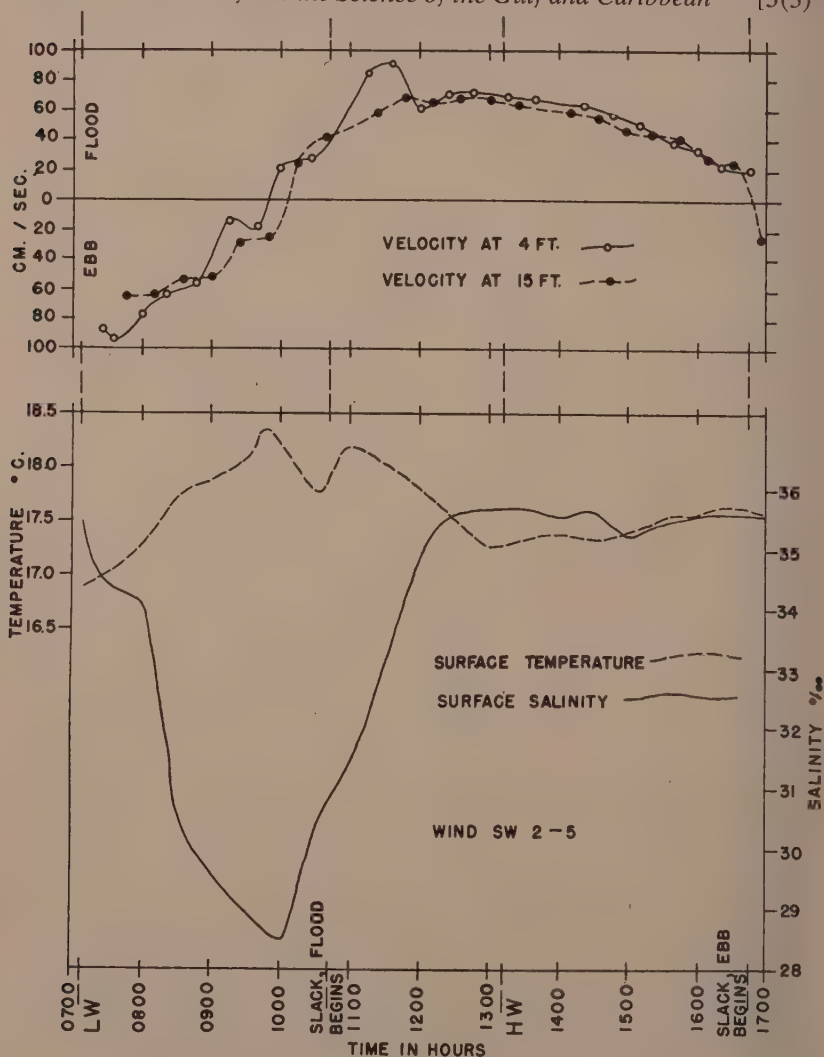


FIGURE 10. Observations at Hatteras Inlet, 25 April 1950.

The trend of the salinity curve in the diagram indicates that, until immediately after we commenced our measurements, the water flowing out on the ebb was undiluted sea water which had moved in dur-

ing the previous flood. Only during the last 2 hours and 40 minutes of the ebb was the salinity less than 35 ‰. The minimum salinity of the ebbing water was 28.5 ‰. Reference to Figure 2, showing the sharp horizontal gradient of salinity about the inlet, suggests that the tidal excursion of the water out of the sound through the inlet was probably less than five miles. During the first two hours of the flood,

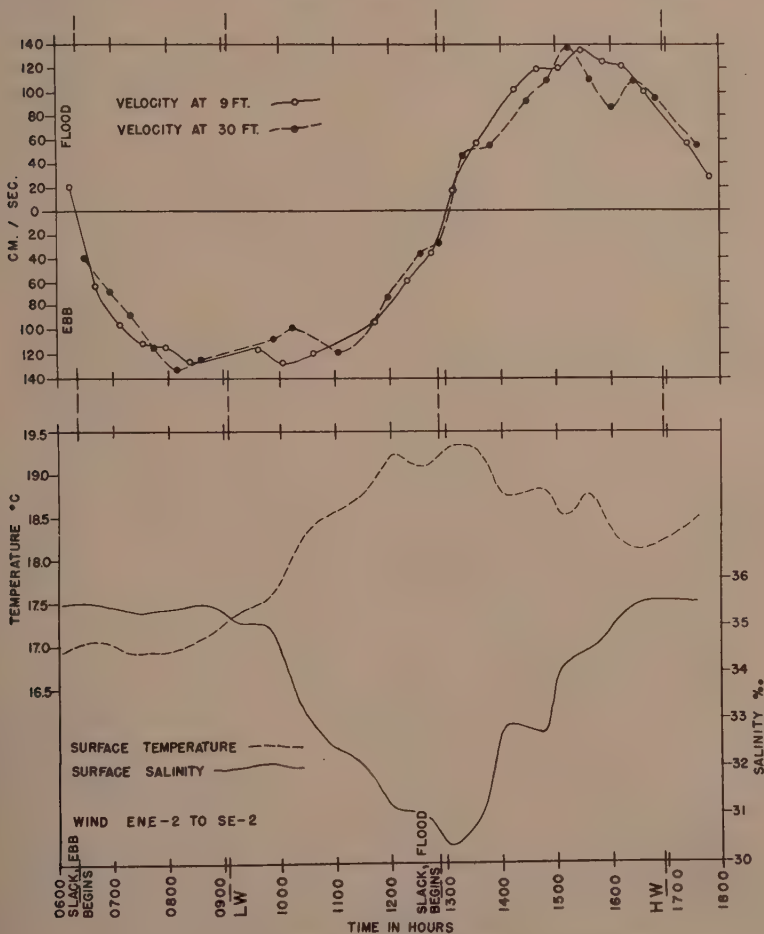


FIGURE 11. Observations at Ocracoke Inlet, 27 April 1950.

diluted sea water was pushed back in through the inlet, allowing nearly five hours for undiluted sea water to flow in.

The current measurements at Ocracoke Inlet on 27 April at depths of 9 and 30 feet in the narrowest part of the channel where the sounding was 38 feet continued for 11- $\frac{3}{4}$ hours, Figure 11. The measurements commenced at the turn from flood to ebb and ended just before the end of the next flood. The ebb commenced at predicted slack, ebb begins, lasted 6- $\frac{3}{4}$ hours with a maximum flow of 134 cm./sec., average of 92 cm./sec. (1.8 kts.). This yielded a transport (assuming gorge of 9,000 m²) of 150×10^6 m³ of water. The current turned just a few minutes after predicted slack, flood begins. The flood was observed for nearly 5 hours with a maximum flow of 137 cm./sec., averaging 80 cm./sec. (1.6 kts.), yielding a transport of 96×10^6 m³ of water. The ebb began 2.5 hours before predicted low water, the flood nearly 4 hours before predicted high water.

As noted for Hatteras Inlet, undiluted sea water flowed out during the first 3.5 hours of the ebb. The minimum salinity flowing out was 30.4 ‰, well above values within 5 miles of the inlet. During the first 3 hours of the flood diluted sea water was pushed back in through the inlet.

The above mentioned current observations are tabulated below:

	Max. Velocity		Av. Velocity		Observed Transport	
	Flood cm/sec	Ebb cm/sec	Flood cm/sec	Ebb cm/sec	Flood x10 ⁶ m ³	Ebb x10 ⁶ m ³
Oregon Inlet	...	138	...	100	...	47
" "	...	...	...	...	56*	64*
Hatteras Inlet	91	94	46	...	65	...
Ocracoke Inlet	137	134	80	92	96	150

*Average of 5 sets of Beach Erosion Board figures on p. 198.

Thus, a rough figure for the inflow through the inlets might be 440×10^6 m³/diem which is approximately eight times the average daily effluent of fresh water from all four rivers.

There probably is no systematic mechanism which regulates the daily salinity increment into the sound. Although the amount of water flowing in and out through the inlets is much larger than the river effluent, much of it appears to oscillate back and forth through the inlets and over the shoals immediately inside. The length and strength of flood and ebb depends on the present and recent winds as well as the semidiurnal tides. The amount of exchange through the inlets must be small, however, for the average salinity of the sound (Fig. 8)

follows roughly the mean monthly runoff from the rivers, as shown above. Inasmuch as the average salinity of Pamlico Sound is roughly 20 ‰ we might assume on an annual basis that the sound is composed of 3 parts runoff and 4 parts sea water. Thus somewhat on the order of $40\text{--}50 \times 10^6 \text{ m}^3$ of undiluted sea water must be added each day, which is about one-tenth of the tidal prism.

TIDE

Except near the inlets, the periodic (astronomical) tides are negligible, U.S.C.&G.S. (1950, p. 298), Beach Erosion Board (1935, p. 25). The nonperiodic rise and fall of water is largely due to the strong winds which blow in the region. The ranges of tide at the inlets are as follows, U.S.C.&G.S. (1949a):

	Mean Range of Tide	Spring Range of Tide
Oregon Inlet	1.8 feet	2.2 feet
Hatteras Inlet	2.0 feet	2.4 feet
Ocracoke Inlet	1.9 feet	2.3 feet

Estimate of Tidal Range in Pamlico Sound. For purposes of conjecture, what is the range of the tide assuming the water flowing in through the inlets were distributed uniformly over the entire surface of Pamlico Sound?

$$\text{If } H = E/A$$

where H is the range of the tide, E is the tidal exchange and A is the area of the sound, we see that, with an inflow of about $220 \times 10^6 \text{ m}^3$ per tide and the area of Pamlico Sound of $44 \times 10^8 \text{ m}^2$, the tidal range is about 5 cm.

Estimate of Wind Tide at the Northern End of Pamlico Sound. It is evident that southwest winds can produce a head of water in the northern end of Pamlico Sound, thus raising the level in the sound higher than the level in the sea outside Oregon Inlet. This is probably the reason that there are no predictions for the time of slack water for Oregon Inlet in the Current Tables (U.S.C.&G.S., 1949b) although there are such for Hatteras and Ocracoke Inlets where the setup is probably much less.

Keulegan (1951) gives an equation for wind tide or setup in natural conditions, where he means by setup the displacement of the waters in an enclosed body of water due to wind friction, as follows:

$$\frac{S}{L} = 3.3 \times 10^{-6} (1 + 63 \left(\frac{H}{L}\right)^{1/2}) \frac{V^2}{gH}$$

where S , the setup, equals $h_2 - h_1$, the windward and leeward displacements h_1 and h_2 , respectively. L is the length of the bay; V , the velocity of the wind; H , the mean depth; and g , the acceleration of gravity in cgs units.

Since the depths vary considerably over the 60 mile length of Pamlico Sound, partial computations have been made for S , S_1 for the windward 46 miles (7.4×10^6 cm.) where the mean depth is 5.2 m., S_2 for the next 8 miles (1.29×10^6 cm.) where the mean depth is 4 m. and for S_3 the leeward section of the sound, 6 miles (0.94×10^6 cm.) where the mean depth is roughly 1 m.

Thus for several wind velocities:

Vel. (kts)		5	10	20	40
S_1	(cm)	6	18	73	292
S_2	(cm)	2	6	23	92
S_3	(cm)	4	13	53	212
ΣS	(cm)	12	37	149	596
Rise (h_1	(cm)	6	18	75	298
in (					
Level (	(ft)	0.2	0.6	2.5	9.8

Hence a southwest wind of about 13 knots is required to provide a setup of about 1 foot. This neglects the funneling effect, caused by the shape of the sound, which must be appreciable. Northeasterly winds will provide a similar rise in level along the southwestern shores.

An estimate of the height of the head of water above mean sea level in the northern part of the sound on a given occasion can be made from the current measurements at Oregon Inlet on 23 April 1950.

If we assume the velocity through the inlet is proportional to the elevation inside minus the elevation outside, this expression would appear as follows:

$$V^2 \sim (h_p - h_s)$$

where V is the velocity at a given time, h_p is the elevation in the sound above mean sea level which we wish to discover, and h_s is the elevation in the sea above or below mean sea level. Since the mean range of tide at Oregon Inlet is 1.8 feet (55 cm.) and the velocity through the inlet at high water was approximately 70 cm./sec. and at low water 120 cm./sec., we have:

$$\text{AT HW } 70^2 \sim (h_p - 27)$$

$$\text{AT LW } 120^2 \sim (h_p + 27)$$

Solving, $h_p = 55$ cm. (1.8 feet) above mean sea level. By Keulegan's method, with an estimated wind of force 4-5 (ca 19 kts.), one would have predicted a setup of 70 cm.

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A CONTRIBUTION TO THE LIFE HISTORY
AND BIOLOGY OF THE SAILFISH, *ISTIOPHORUS*
AMERICANUS CUV. AND VAL.,
IN FLORIDA WATERS¹

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ABSTRACT

Thirteen specimens of post-larval and juvenile stages of the Western Atlantic sailfish, *Istiophorus americanus*, are described, ranging in standard length from 3.9 mm to 208.0 mm, and ten specimens are illustrated, all from the Florida Current. These are compared with previously published descriptions and illustrations of young Istiophoridae. The developmental changes from post-larval to adult are described and the general biology is discussed. Florida populations of sailfish spawn during the early summer near shore and no migrations are observable in Florida waters. The food and methods of feeding are described and the results of tagging operations are given.

INTRODUCTION

The present study is part of the results obtained from a continuing study of the life histories and biology of Florida fishes, especially the food and game fish, supported by the National Geographic Society and the Florida State Board of Conservation, and carried out by the Marine Laboratory of the University of Miami.

In 1948 the Marine Laboratory, at the request of the Florida State Board of Conservation, initiated a study of the biology of the sailfish in Florida waters in an attempt to solve certain conservation problems relating to this important gamefish. This study was set in progress by the present writer who carried it through for a period of one and a half years. From that period to date the program has been carried out by Melvin Light, Winfield Brady, and H. P. Mefford, all of the fisheries section of the Marine Laboratory.

During this period a tagging program was set up with the end in view of determining migrations and of settling the question of whether or not sailfish continue to live after releasing by sports fishermen. In conjunction with this, as many fish as were obtainable were measured by the field workers at the fishing piers. Later, a large scale investiga-

¹Contribution No. 116 from the Marine Laboratory, University of Miami.

tion of the stomach contents of sailfish was begun and this was finally expanded to include gonadal studies.

In 1953 the National Geographic Society initiated a program to be carried out by the Marine Laboratory on the larval, post-larval and juvenile stages of the fishes found in the plankton of the Florida Current, with particular reference to the food and game fish. In the progress of this work a few small stages of the Western Atlantic sailfish, *Istiophorus americanus*, were obtained. These small stages were supplemented by larger stages donated by Mr. J. T. Reese, taxidermist, of Fort Lauderdale. Two gaps in the series were finally filled by specimens kindly loaned by Captains Fred Stone and Vivian Bonnert of Boynton Beach, Florida. A small series of early stages was kindly supplied to the author through the courtesy of Luis R. Rivas, University of Miami Marine Laboratory.

While the taxonomy of the Florida species of sailfish is still in question, the present author has conformed to the latest usage and applied the name *Istiophorus americanus* Cuvier and Valenciennes, to the species found in our waters. Further study on this question is now being carried out by other investigators.

For help in collecting data, specimens, and much valuable information the author wishes to thank not only the institutions and individuals named above but also Al Pflueger, taxidermist, of Miami, Lex Woolbright of Boynton Beach, Florida, and the countless charterboatmen and sports fishermen of the Florida coast who have contributed to the study.

EARLY STAGES

A survey of the literature of the sailfishes quickly indicates that the genus *Istiophorus* as a whole is sadly in need of taxonomic revision, despite the fact that they have long held a high place among the important sport fish of the world. The many names applied in the literature, the uncertainties regarding synonymies, and the confusion regarding the presence or absence of certain sailfishes in our waters, makes the identification of early stages of this fish extremely difficult. This is magnified by certain other considerations, namely the apparently complete ignorance as to the appearance of the very early stages of the blue marlin, *Makaira nigricans ampla* (Poey), the white marlin, *Makaira albida* (Poey), and the spear fish, *Tetrapterus belone* Rafinesque. Of these, the first two are well known as adults from our area and the last is apparently a little known but occasional visitor. Until

the post-larval and juvenile stages of these fish are known the danger of confusing these with the early stages of the sailfish seems to the present author to be of prime consideration.

The Western Atlantic sailfish, *Istiophorus americanus*, was first described in the literature by Cuvier and Valenciennes in 1831, apparently from a short description and rather poor figure in Piso's "Historia Naturalis Braziliae" published in 1648 at Amsterdam.

Both De la Sagra (1853) and Poey (1858, 1863) mentioned the sailfish as occurring along the coast of Cuba and Schomburgk (1848) listed it as having been found at Barbados.

In 1872 a specimen was taken off Newport, Rhode Island and the skeleton and a painted plaster cast was deposited in the U. S. National Museum in Washington, D. C.

Apparently the first record of its occurrence off Florida was a specimen caught in 1873 which was brought from Key West to New York City. Two other specimens were captured in 1878 between Indian River and Savannah and taken to the latter city where they aroused much interest.

Goode (1883) in his masterly work "Materials for a history of the sword fishes" was the first to survey the knowledge of the sailfish and it is from this work that much of the above brief history is drawn.

Records of this species were quite meager and scattered until recent years when this fish became one of the most popular game fishes of the world. Since the late 1920's it has become increasingly important as a fisheries along the S. E. Florida coast but few accurate scientific observations have been made and to date less is known concerning this fish than is known of many less important species.

In the last few years a new and important sailfishing center has arisen in the Gulf of Lower California. The sailfish caught there is apparently distinct from our species and reaches a considerably larger weight and length.

Some systematists consider that there are but two species of sailfishes found throughout the world, the Atlantic sailfish, *Istiophorus americanus*, and the Pacific sailfish, *I. greyi*, and it has even been suggested that there is only one species, *I. americanus*, and that the others are only geographical races of this species.

However, at the present time, the author agrees with Lamonte and Marcy (1941) in recognizing four other species of sailfish: *I. immaculatus* (Ruppell) Indian Ocean and Red Sea, *I. greyi* Jordan and Hill from Peru to Lower California, *I. orientalis* (Temminck and Schlegel)

from Japan and Hawaii, and *I. brookei* Fowler from Tahiti.

Gunther (1873-74) apparently was the first to publish figures of post-larval and juvenile sailfish. His specimens ranged from 9.0 mm to 14.0 mm and 60.0 mm and came from the "South Sea," in this case the tropical Atlantic. Lutken (1880) figured a specimen of about 5.5 mm and described another of 21 mm out of a series of about 5 specimens, also from the tropical Atlantic. In 1941 Lamonte and Marcy figured a specimen from the eastern Pacific 16.5 mm in length. The same year Beebe published a paper on young sailfish taken by the *Arcturus* in the eastern Pacific and figured, in series, all of the young specimens so far figured in the literature including Ruppell's (1871) specimen from the Red Sea, and Cuvier and Valenciennes' juvenile from the West Coast of Africa.

Beebe's illustrated series represents all of the post-larval and juvenile stages of the genus *Istiophorus* known to date. It is of primary value in illustrating the general developmental history of the genus, if it is assumed that all of the younger stages are actually young specimens of *Istiophorus*.

A close examination of these figures shows a considerable amount of variation and discrepancies within the series which is the result of comparing specimens of several species (and perhaps genera). Of the ten specimens illustrated, only one, (figure 1a) may perhaps be the young of *Istiophorus americanus*. This is Lutken's specimen from the North Atlantic.

Figures b, c, and f are from Gunther and either are not sailfish or represent another species. The extreme difference in the lengths of the upper pterotic spine and the lower preopercular spine is very noticeable.

Figure h represents Cuvier and Valenciennes' specimen from the west coast of Africa north of the Cape of Good Hope (between the Cape of Good Hope and France?). With our present knowledge of the sailfishes it is probable that this also does not represent *Istiophorus americanus*.

Figure i is Ruppell's *Histiophorus immaculatus* from Djetta on the Red Sea. This is presumably a distinct species occupying the Indian ocean and the Red Sea and shows some certain differences from our species.

The remaining specimens, figures d, e, and g, are from the Eastern Pacific and presumably represent the young of *Istiophorus greyi* Jordan and Hill. Figure j is of an adult of this species.

A survey of the above figures and comments discloses that to date there are no series illustrated or described of the post-larval and juvenile stages of the Atlantic sailfish.

FLORIDA AND BAHAMA SPECIMENS

During the past year the author has had available to him a series of small post-larval sailfish ranging in standard length from 3.9 mm to 208.0 mm represented by 13 individuals. Eight of the specimens were obtained in good condition from the stomachs of dolphin; six from off Fort Lauderdale, Florida and two from off Boynton Beach, Florida. Of the remaining five, two were from off Gun Cay light, Bahamas and three from off Bimini, Bahamas. Thus all of the specimens involved are from a distance represented by a radius from Miami of not over fifty miles. As a result of this homogeneity of background it is considered that they represent a single species of sailfish, *Istiophorus americanus*, and thus their value is considerably enhanced when attempting to interpret the development of other known specimens.

Twelve of these specimens are represented in the accompanying figures which were drawn by the author from the material in formalin. General growth changes, gross morphology and body changes may be seen quite easily by referring to the figures. In addition 12 measurements were obtained from each specimen (Table I) and from these raw data indices were derived which were used in constructing the accompanying graphs.

No detailed descriptions are given of the specimens as both time and space make this prohibitive in the present paper but certain remarks are deemed necessary to interpret the growth changes observed.

Specimen No. 1. (Figure 1, A). 3.9 mm standard length, obtained in plankton tow 5 miles west of Gun Cay, Bahamas on surface at 1040, July 2, 1953.

Remarks: This is the smallest known specimen of Istiophorid and is presumed to have only recently hatched from the egg. The snout is very short, jaws almost equal, and the opercular spines are rather short and subequal. The fins are still united with the tail and present a continuous contour line with only a hint of the coming indentation at the base of the caudal fin. The pelvic fins are not discernable even as rudiments. The fin elements in general are lacking. The eye is smaller than in later specimens and the vertebral column is straight and rod-like, tapering to a point caudally with no trace of an upturn.

TABLE NUMBER I.

MEASUREMENTS, IN MILLIMETERS, OF THIRTEEN POST-LARVAL AND JUVENILE SPECIMENS OF THE ATLANTIC SAILFISH,

Istiophorus americanus

Specimen No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Standard length	3.9	4.8	5.5	6.3	8.0	15.0	19.5	20.0	20.5	29.5	37.5	70.0	208.0
Total length	4.2	5.4	6.5	7.3	9.6	16.7	22.0	21.5	22.0	32.5	41.0	76.0	234.0
Greatest depth	1.2	1.6	0.7	1.9	2.4		3.5	3.2	3.2	4.0	4.2	7.0	15.0
Head length	1.5	2.2	2.7	3.8	4.2	7.5	9.7	9.8	10.9	15.9	18.6	39.0	94.0
Snout Length	0.5	0.6	0.8	1.2	1.3	3.8	5.0	5.0	5.7	10.0	12.4	28.7	76.0
Eye diameter	0.5	0.7	0.9	1.1	1.3	1.6	2.0		2.0	2.4	2.8	3.7	
Pterotic spine	0.4	0.8	0.9	0.8	0.8	0.8	0.7	0.8	1.0	1.0	1.1	0.4	
Preopercular spine	0.7	0.3	1.4	1.9	1.1	2.6	2.5	2.3	2.3	2.6	2.8	2.2	
Length upper jaw	0.8	1.4	1.8	2.2	2.4	6.2	7.5	7.0	8.0	12.7	15.4	32.5	192.0
Length lower jaw	0.7	1.2	1.8	1.9	2.3	5.1	5.6	6.2	5.8	7.5	8.9	12.5	37.0
Pelvic fin length			0.2		0.8	1.6	4.0	2.2	3.5	6.4		15.0	46.0

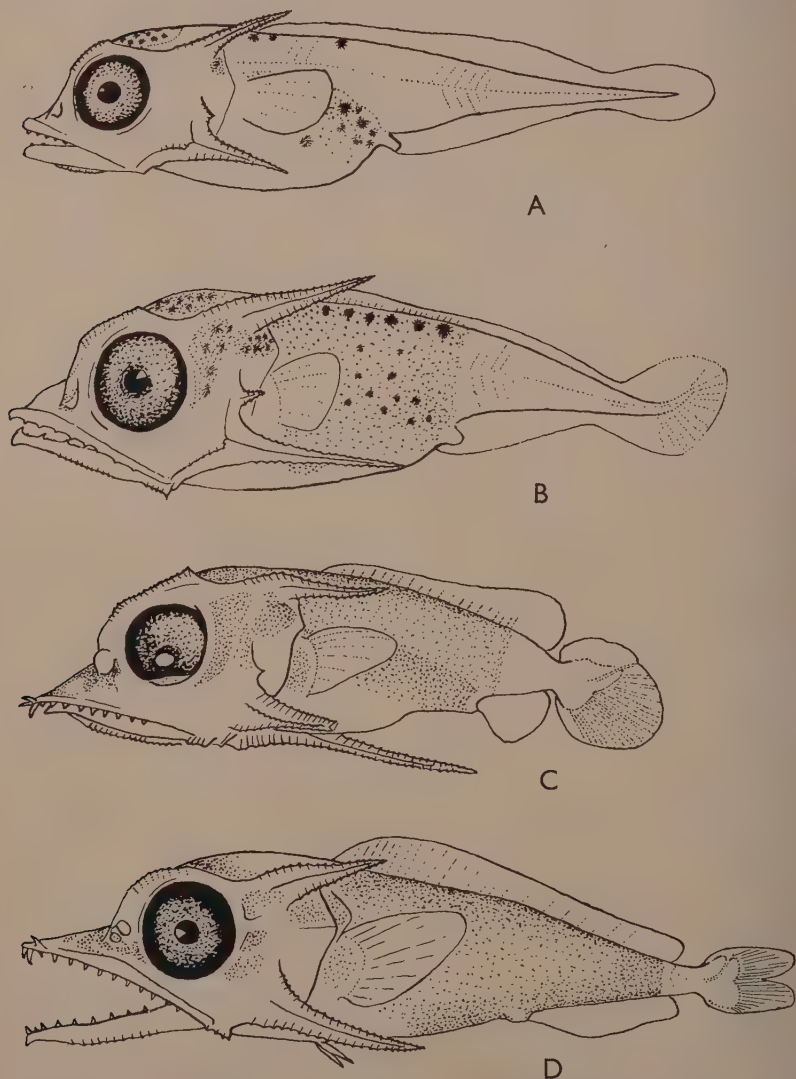


FIGURE 1. Post-larval stages of the western Atlantic sailfish, *Istiophorus americanus*, from the Florida Current. A, Specimen 3.9 mm. standard length; B, Specimen 4.8 mm. standard length; C, Specimen 6.3 mm. standard length; D, Specimen 8.0 mm. standard length.

The ocular crest is poorly developed but the opercular spines are serrated. There are a few scattered chromatophores in the dorsal area of the head. Teeth, although present in the jaws, are few and not strongly developed. A noticeable second preopercular spine somewhat above the base of the ventral spine is beginning to develop. The stomach is rather distended, giving a suggestion of plumpness to the specimen but this, as in all of the individuals of the series, is due to gorging with food. Despite the small size of the specimen, four copepods were removed from the stomach.

Specimen No. 2. (Figure 1, B). 4.8 mm standard length, obtained in plankton tow 5 miles west of Gun Cay, Bahamas, on surface at 1838 on June 11, 1953.

Remarks: Several changes are now apparent. The dorsal and ventral fins are more strongly differentiated from the caudal fin which is now enlarging and becoming fan shaped. The supraocular crest is well distinguished and serrated, but as shown here and in later specimens of the series, it bears no resemblance to the condition shown in Lutken's figure and it is not ciliated as observed by Gunther. The upper pterotic and lower preopercular spines are strongly keeled and serrated and the second preopercular spine is well developed. The snout is beginning to lengthen, the eyes are enlarging and the nostrils are becoming evident. The teeth in the jaws are strongly developed and a papilla is present on the tip of the lower jaw. The mandible is serrated on its lower edge, a condition which is retained for some time. The vertebra is turned upward caudally and caudal fin elements are beginning to form. No pelvics are as yet in evidence.

Specimen No. 3. (Figure 2) 5.5 mm standard length, obtained in plankton tow at a station on the edge of the Florida Current off Gun Cay, Bahamas, by L. R. Rivas, May 29, 1953.

Remarks: In this specimen the fins are slightly less developed than in the preceding 4.8 mm specimen and the vertebral column is straight and rod-like. The caudal fin is still homocercal as in the 3.9 mm specimen but the pelvic fins appear as minute buds between the bases of the pectorals. The pectoral elements are differentiating as are the caudals. The snout has lengthened slightly, the teeth are more prominent and the body is much more heavily pigmented in distinct areas. The second preopercular spine is short but stout and distinct, serrated as is the preopercular spine and the pterotic spine. Otherwise there are few changes from the preceding specimen.



FIGURE 2. Dorsal view of a post-larval specimen of the western Atlantic sailfish, *Istiophorus americanus*, 5.5 mm. standard length, showing details of pigmentation and arrangement of spines.

Specimen No. 4. (Figure 1, C), 6.3 mm standard length, obtained in plankton tow at surface on the edge of the Florida Current off Bimini, Bahamas, by L. R. Rivas, June 12, 1952.

Remarks: At this stage the height of post-larval development has been

reached (see graphs) and the fish is most differentiated from the adult form. The snout is definitely elongating, the lower jaw is shortening in comparison to the upper jaw and the opercular spines are at their greatest development with the exception of the second preopercular which is disappearing. The dorsal and ventral fins are separated from the caudal fin and the elements are appearing. The hypural bones are developed but not in the finished shape and the vertebral column is no longer distinctly visible. The eye diameter is slightly decreasing and the teeth are strongly developed and prominent. The supraocular crest is strongly serrated and the lower jaw or mandible bears a conspicuous serrated ridge on the ventral surface with strong serrations at the juncture of the jaws. The nostrils have not as yet separated but the general orifice is large.

Specimen No. 5. (Figure 1, D), 8.0 mm standard length, obtained in plankton tow at surface on the edge of the Florida Current off Gun Cay Light, Bahamas, by L. R. Rivas, May 29, 1953.

Remarks: The most noticeable change is the elongating and slimming of the body, elongation of the snout and the first appearance of a forking of the caudal fin. The hypurals are fully developed, the fin elements are becoming more evident and the long line of the dorsal fin is somewhat higher relatively, but there is still no indication of the greatly increased length of the anterior edge of the dorsal which will appear in the next stage. The reduction in size of the anus is quite noticeable. The nostrils are doubled and well developed with an angled band which separates them. The teeth have become differentiated into large strong teeth few in number interspersed with smaller very sharp needlelike secondaries. The lower preopercular spine is much the larger and all traces of the secondary preopercular spine have disappeared. The pectoral fin which until now has shown little change has increased in size and become somewhat elongated and the pelvic fins are becoming conspicuous but no indication of a ventral sheath is evident.

Specimen No. 6. (Figure 3, A), 15.0 mm standard length, obtained from the stomach of a dolphin, *Coryphaena hippurus*, caught by the charter boat *Vicamus*, Captains Vivian Bonnert and Fred Stone, off Boynton Beach, Florida in the summer of 1951.

Remarks: As can be seen by referring to the figure at this stage adult characters are now in evidence. The dorsal fin is definitely large and

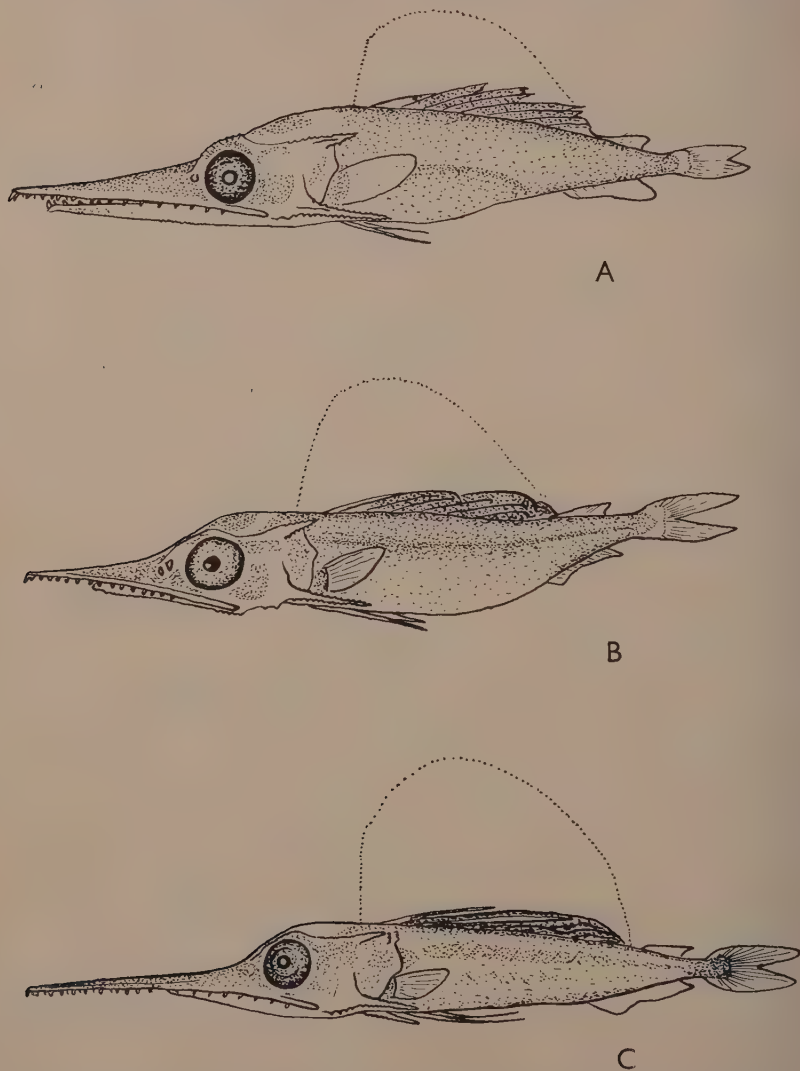


FIGURE 3. Post-larval stages of the western Atlantic sailfish, *Istiophorus americanus*, from the Florida Current. A, Specimen 15.0 mm. standard length. B, Specimen 19.5 mm. standard length. C, Specimen 29.5 mm. standard length.

of sailfish proportions, the dorsal finlet is beginning to become differentiated from the dorsal fin and the ventral fin and finlet are becoming separated. The caudal fin is well forked but not spread and the pelvic fins are rapidly increasing in length and are very slender. Both dorsal and ventral fins are equipped with body slots for their reception. The snout is becoming exaggerated in size, the lower jaw shortening and the teeth are becoming relatively smaller. The ocular crest is still present and serrated but the upper pterotic spine is now much shorter and showing indications of eventual disappearance. The lower preopercular spine no longer projects downward and outwards as previously but is directed posteriorly in nearly a straight line while adhering closely to the body.

Specimen No. 7. (Figure 3, B), 19.5 mm standard length, obtained from the stomach of a dolphin, *Coryphaena hippurus*, taken off Fort Lauderdale, Florida, July 7, 1947. Collected by Joseph Reese.

Remarks: The most noticeable feature of this specimen is the height of the dorsal fin which now has the proportions of the adult "sail" though not its shape. The dorsal finlet is separated from the dorsal fin but is not developed as such; the ventral is still united to the ventral finlet. The caudal fin is now well-forked but is not spread, an event which occurs at a much later stage. Serrations are still visible upon the supraocular crest, but the crest itself is slowly reducing in size. The nostrils are fully developed and separated, and the upper and lower jaws are well equipped with teeth. Other characters are much as in the former stages.

Specimen No. 8. 20.0 mm standard length, obtained from the stomach of a dolphin, *Coryphaena hippurus*, taken off Fort Lauderdale, Florida, July 7, 1948. Collected by Joseph Reese.

Specimen No. 9. 20.5 mm standard length, obtained from the stomach of a dolphin, *Coryphaena hippurus*, taken off Fort Lauderdale, Florida, July 7, 1948. Collected by Joseph Reese.

Specimen No. 10. (Figure 3, C), 29.5 mm standard length, obtained from stomach of a dolphin, *Coryphaena hippurus*, taken off Fort Lauderdale, Florida, July 7, 1948. Collected by Joseph Reese.

Remarks: There is so little change in the three above specimens that they are here considered together. The dorsal fin is greatly enlarged and entirely separated from the dorsal finlet which now has nearly the

adult characters. The ventral fin and finlet are still united. The pelvic fins are long, slender and appear to be much as they are found in the adult. The upper spine of the opercle is much reduced while the lower preopercular spine is still quite noticeable. The supraocular crest is much reduced, without serrations, and is showing signs of ultimate loss. The upper jaw is now recognizable as the "bill" of the adult and the lower jaw is much shortened, but both are still toothed. The eye diameter is now greatly reduced and will show a steady diminishing to the adult. At this stage two small serrated "scales" are found just posterior to the pterotic spine. There are indications that such may be forming in younger forms and in older stages it is lost.

Specimen No. 11. (Figure 4, A). 37.5 mm standard length, obtained from stomach of a dolphin, *Coryphaena hippurus*, taken off Fort Lauderdale, Florida, July 7, 1948. Collected by Joseph Reese.

Remarks: This specimen shows nearly all of the adult characters. The ventral fin and finlet are separating as shown by the strong indentation in the general outline, the pectoral fins are becoming more slender and elongate and the pelvics are still growing. Of the larval characters surviving the two opercular spines are much reduced although the lower preopercular spine is still prominent, and the jaws are still rather strongly toothed. The supraocular crest is reduced to a bony ridge surrounding the upper edge of the orbit.

Specimen No. 12. (Figure 4, B), 70.0 mm standard length, obtained from the stomach of a dolphin, *Coryphaena hippurus*, caught by the charter boat *Vicamus*, Captains Vivian Bonnert and Fred Stone, off Boynton Beach, Florida, in the summer of 1951.

Remarks: This is an exceptionally well preserved specimen retaining all of the characters in good condition. At this stage the post-larval characters are nearly gone and the young juvenile characters are in the ascendancy. The upper jaw is greatly elongated but is still sparsely toothed. The lower jaw is greatly shortened as in the adult but is equipped with minute teeth or spinelets with serrations on the under side. The upper pterotic spine is reduced to a mere point and the lower preopercular spine, while still noticeable has lost its serrations along the edges. The dorsal fin or "sail" is fully developed but the ventral fin is still slightly united to the ventral finlet. The caudal fin is beginning to strengthen and spread and the pelvic fins are long, slender, and approaching the adult condition.

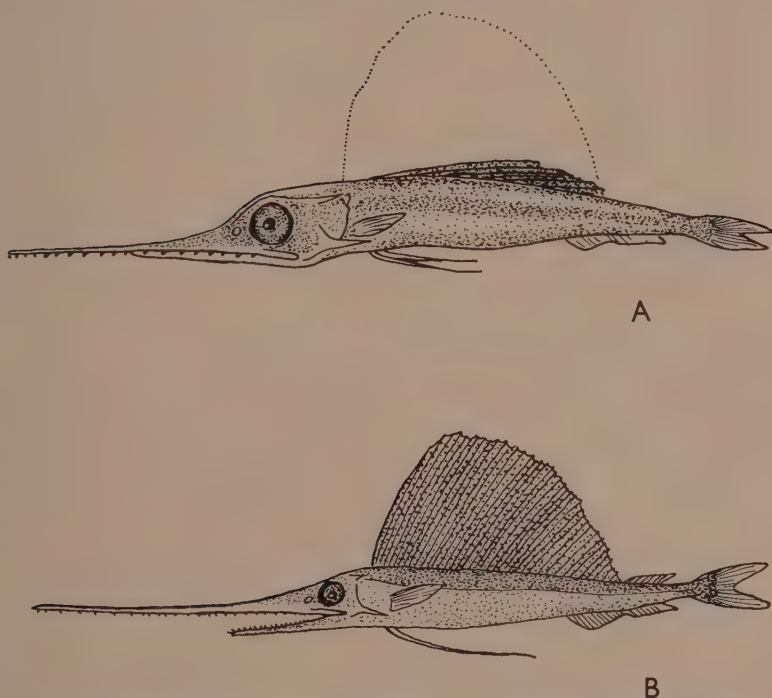


FIGURE 4. Post-larval and juvenile specimens of the western Atlantic sailfish, *Istiophorus americanus*, from the Florida Current. A, Post-larval specimen 37.5 mm. standard length. B, Juvenile specimen 70.0 mm. standard length.

Specimen No. 13. 208.0 mm standard length, obtained from stomach of dolphin, *Coryphaena hippurus*, caught off Fort Lauderdale, Florida, March, 1951. Collected by Joseph T. Reese.

Remarks: At this stage all larval or post-larval characters have been lost and the fish is a young juvenile. The opercular spines have disappeared, the finlets are completely separated, the pelvics in the adult condition, and the caudal fin completely developed. In this stage the fish are still quite differentiated from the adult form by the bodily proportions which from this stage on will slowly change, making a rather distinct break at a length of about four feet, to become an adult. At this stage it is characterized by the extreme length of the upper jaw, and the extreme slenderness of the body. An analysis of

the changes at this point and later are best shown by graphing the bodily proportions and these will be discussed later.

Discussion. A study of the above remarks and an examination of the accompanying figures and graphs disclose a number of discrepancies between the present specimens and the few specimens previously reported or figured in the literature. Lutken's (1880) specimen, because of its capture in tropical Atlantic waters, has been presumed to be a post-larval *Istiophorus americanus*. An examination of both the original illustration (Lutken 1880, pl. 2, fig. 11) and the facsimile reproduction by Goode (1883, pl. 17) shows that this specimen, with a length of 5.5 mm, does not agree, except superficially, with our specimen of 5.4 mm total length (Figure 1, B). In Lutken's specimen the most striking dissimilarities are the absence of the secondary preopercular spine and the shape of the supraorbital crest. In this specimen the latter character varies strongly. The crest is circumorbital, following the outline of the orbit; it is strongly dentate, and has a posterior tooth at the upper angle. It apparently does not enclose the developing nostrils and posteriorly does not continue back to unite with the upper pterotic spine. In addition to these differences there is in Lutken's specimen a ventral preopercular spine which is absent in all of our specimens.

Other differences may be observed: the very short and poorly developed dorsal fin which is less than half the length of the body, the nearly equal opercular spines, the lack of serrations on the lower edge of the mandible, and the straight vertebral column which has not yet begun to develop into the hypurals. The detail with which this specimen is figured would seem to indicate that it was painstakingly done and with great accuracy, yet the variations shown from our specimen are so strong that it seems to the author to preclude its association with *Istiophorus americanus*. It may perhaps be the early stage of *Makaira* or *Tetrapterus*, neither of which are known at present.

An examination of Goode's (1883) reproductions of Gunther's figures from *Fishes of the South Sea* (1873-74) show many strong differences from the present specimens. In all of these specimens the upper pterotic spine is much smaller than the lower preopercular spine and they are both figured and described as being ciliated on the spines and supraocular crest, rather than strongly serrated as the present specimens show. In addition Gunther's specimens show a much stouter and heavier "bill." In the specimen of 60.0 mm the

preopercle shows spination not found in the present specimens and the "bill" is devoid of teeth beyond the end of the mandible.

An examination of Beebe's series (1941: p. 210) shows that Gunther's specimen (figure f) certainly bears little resemblance to either the preceding specimen which is smaller or the following specimen which is larger. It seems doubtful to the author if this specimen actually represents an *Istiophorus* but rather a *Makaira*. Deraniyagala (1952) has figured a juvenile *Istiophorus gladius* (Broussonet) of 127 mm in length from Ceylon which indicates that this species could hardly be confused, at least in this stage, with those under discussion.

GENERAL DEVELOPMENT

In reading through the description of the changes which occurred in the young stages it can be seen that certain characters, as is expected, are larval characters which disappear at around 100.0 mm while others, which are retained in the adult, are not discussed. In order to show graphically the changes which occur from hatching to adult a series of graphs were constructed (Fig. 5; Fig. 6, A-D) and these will be discussed below. In interpreting the graphs it should be borne in mind that a total of 123 specimens, both post-larval, juvenile and adult were plotted. In all of the graphs, each separate dot represents a single individual up to and including the 208.0 mm specimen. Beyond this length the dots represent 1 specimen only in three cases, the others represent from 2 to 21 specimens each.

Rather than examine and discuss each graph separately, certain important developments and trends can best be discussed by a general examination. It can be seen that there are three important stages in the life of *Istiophorus americanus* which correspond to the post-larval, juvenile and adult stages, and which are revealed by rather strong changes in most of the plotted characters (Figure 6, A).

The most noticeable change in the characters, with the exception of the snout and pelvic fin length, occurs in the post-larval stage at a length of from about 4.8 to 10.0 mm with a mode of about 6.0 mm. It is unfortunate that only five specimens near this range were available and it is hoped that future work by others will confirm and more clearly delimit these changes.

At this stage the fish are fat, short-billed, long spined individuals with large heads and enormous eyes. The pelvic fins are only just beginning to develop. It is at this size that they present a very charac-

teristic form which easily distinguishes them from other larval or post-larval fish (bearing in mind the possibility of *Makaira* and *Tetrapterus* having similar stages).

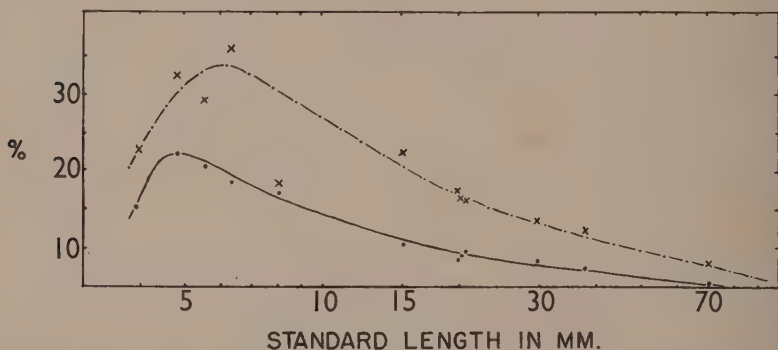


FIGURE 5. Graph depicting the relationship of length of upper pterotic spine and lower preopercular spine to standard length during growth. Solid line represents upper pterotic spine, broken line represents lower preopercular spine.

At about 7.0 to 8.0 mm these characters are beginning to undergo changes which will lead into the juvenile stage which is fully developed between lengths of about 50.0 mm and 300.0 mm with the height of "juvenileness" at about 100.0 mm. At this stage the only post-larval characters which still persist are the jaw teeth and the opercular spines and at about 100.0 mm these are finally lost.

The fish at this length is long and slender with a body depth of only 7 percent of the standard length. One of the most conspicuous features is the excessively long snout and bill. The snout length is 42 percent of the standard length and is higher than is ever attained again even in those aberrant adults sometimes seen with exceptionally long "bills". The dorsal fin or "sail" is here fully developed in the 208.0 mm specimen and also in the 70.0 mm specimen. The final shape has been attained and the characteristic colors are fully revealed.

As is to be expected, the changes from the juvenile stage to the adult take place gradually as this is accomplished during a long period of growth. Due to the use of 4 cycle semi-log paper this latter development appears to take place over a short range of length but this is due to the shortening effect of the scale. There are no abrupt

or clearly definable points in the change from juvenile to adult: the slenderness of the body slowly modifies and weight and corresponding girth and depth never become as great as in the marlins or as much so as in *Istiophorus greyi* or *I. immaculatus*.

The spear or bill gradually shortens in relation to the overall length of the fish, dropping from 42 percent of the standard length to an adult 25 percent of the standard length. The eye diameter which in the post-larval fish was as high as 18 percent of the standard length dropped to about 4 percent in the juvenile and ultimately becomes stable at about 2 percent in the adult.

An examination of the graph of body depth (Figure 6, D) shows a great deal of change taking place during growth with a peak of 34 percent and a low of 7 percent. In the adult fish, however, there appears to be a tendency for another drop in depth. There is a steady gain in depth up to about 1800.0 mm where a depth of 14 percent is obtained. From this point onwards there is a slight regression and in sailfish of over 8 feet (2193.0 mm) it has dropped to about 12.8 percent.

In the above description of the development and changes which take place in the life history of *Istiophorus americanus*, it should be borne in mind that the addition of more extensive measurements than have been attained at present may somewhat change the picture as it is now seen but it is believed by the author to be substantially as represented.

Many more characters have been measured of adult and late juvenile stages than those given in the graphs but as these have their major importance in systematic work in the determination of species or races, it was not thought advisable to burden the present paper with them. They are however on file in the library of the Marine Laboratory, University of Miami, and it is expected that these data will be employed subsequently by staff members now engaged in a systematic study of the group.

From incomplete studies of length and weight frequencies of about 225 sailfish landed in 1948, it is indicated that the average length of adult sailfish caught on our coast, is around 7 feet; a length suggested by an abrupt mode in the frequency graphs. The average weight at this length is difficult to determine due to the great variation in these fish. They appear to vary in weight from a low of 24 pounds to a weight of 58 pounds but an average of around 40 pounds is indicated by our data.

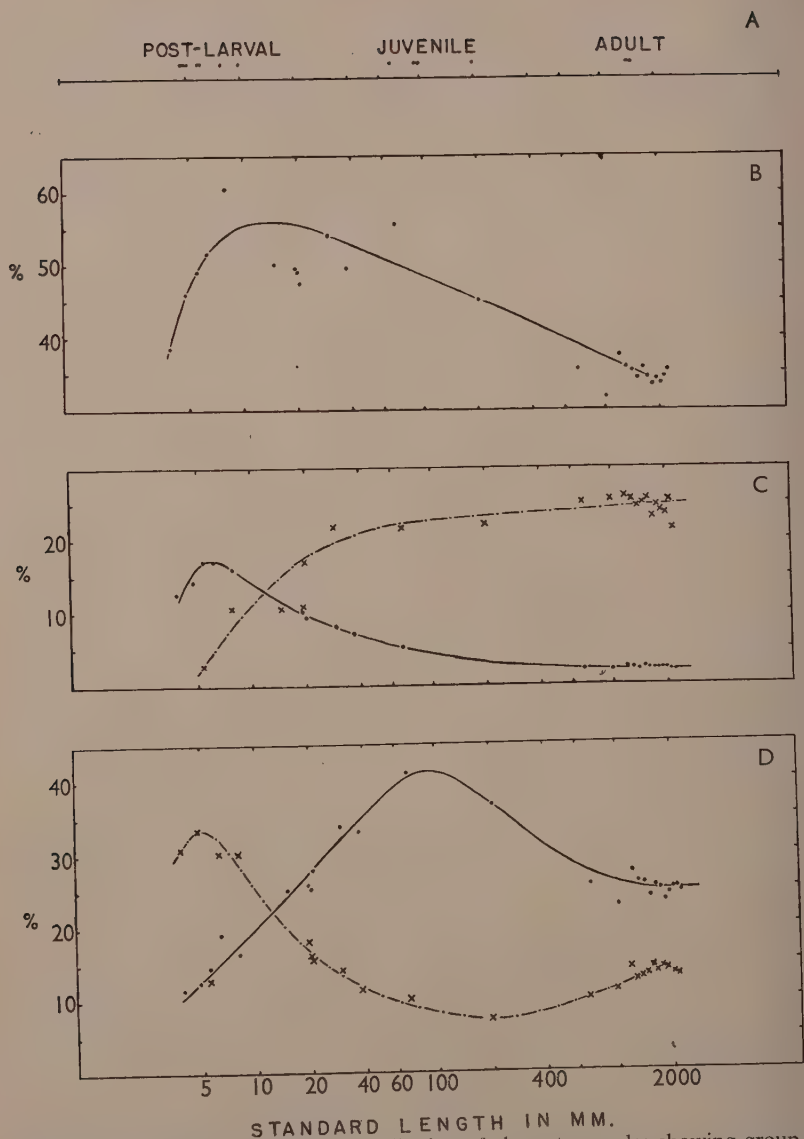


FIGURE 6. Graph A. Frequency distribution of character modes showing grouping with size, correlated with the post-larval, juvenile, and adult stages. Graph B. Relationship of head length to standard length during growth. Graph C. Relationship of orbit diameter and pelvic fin length to standard length during growth. Solid line denotes diameter of orbit, broken line denotes pelvic fin length. Graph D. Relationship of snout length and depth of body to standard length during growth. Solid line denotes snout length, broken line denotes body depth.

According to the International Game Fish Association, the record Atlantic sailfish weighed 123 pounds and was caught off Walker's Cay, Bahamas by Herman Teetor in 1950. Sailfish on our coast are not uncommon over 8' and a few individuals around 8'6" are caught each year.

SPAWNING

LaMonte and Marcy (1941) have summarized the present information concerning the spawning of the Atlantic sailfish and it is very meager. Hunt (1935) states "All the sailfish anglers of experience, and all the guides and taxidermists I know are agreed that the breeding season off Florida is during late June". The taxidermist Al Pflueger, quoted by Kaplan (1937) says "Sailfish breed in the Gulf Stream off Miami during May and June, the weight of roe in them being 4-8 pounds, according to size: and sailfish of 2 to 10 pounds are found here from Thanksgiving Day to Christmas."

Farrington (1950) adds no original information but remarks "Very small specimens have also been found and it has been pretty well established that these fish breed somewhere in the waters off Florida and the north coast of Cuba. Tiny sailfish have been taken from the stomachs of dolphin and other fish."

In the Gulf of Mexico Baughman (1941) reports "Several female fish taken later in the season have had spawn running from them. Of the eighteen fish taken at Port Isabel between August first and third, inclusive (1940) 17 were females, with roe in all stages of development." On the Gulf coast of Florida, LaMonte and Marcy (1941) report that schools of sailfish averaging 8 inches to one foot are common off Tarpon Springs. The validity of this latter report is suspect as the author has spent several years continuously on the water in the vicinity of Tarpon Springs and has never either seen such schools or heard reports of them.

From the literature it can be seen that it has previously been considered, mostly through capture of gravid females, that the sailfish breed near or off the Florida coast and the consensus of opinion gives the time as the early summer. The author disagrees with Pflueger, however, that spawning takes place in the Gulf Stream. The number of sailfish actually caught within the boundaries of the Gulf Stream is very small in comparison with the number caught inshore, in the waters between the edge of the Stream and the beach, and the author's own experience indicates that the fish approach the shore to breed.

In the summer of 1940 the author operated a sailfishing boat from Boynton Inlet, Florida, about ten miles south of Palm Beach. During a period of prolonged calm weather, in June and early July about fifteen sailfish were hooked, part of them released after being brought to the boat. These fish were all very heavy gravid females and so close to spawning that they gave very little fight, most of them never jumping but merely breaking water. These fish were caught in an area extending northward for about two miles from the inlet and all within a distance of not over 200 feet from the beach in shallow water over sandy bottom with scattered flat beach rock reefs. The roes of these fish were all extremely large and very ripe. During this period the author often sighted two and three fish at a time swimming slowly in the shallow water. It was assumed, due to the ripe ovaries and sluggish disposition, that the fish were spawning.

In confirmation of these observations is a statement by Mr. George De Bay of Palm Beach that in late May or early June of 1933, he saw a pair of sailfish breeding. The fish were swimming slowly along the inside edge of the shallow reef just off the end of the Palm Beach pier and were pressed tightly together. Mr. De Bay threw a spear into them and landed the female which measured seven feet seven inches in total length (with the top fork of the caudal fin bent straight as is customary), weighed 70 pounds, and contained a very ripe roe which weighed approximately seven pounds (an average sized ripe roe).

Indications from the post-larval and young specimens reported upon in this paper also confirm this spawning time. Specimens from the eastern side of the Gulf Stream, the smallest in the series, with standard lengths ranging from 3.9 to 8.0 mm were caught from May 29 to July 2. Specimens from off Fort Lauderdale, Florida ranging in standard length from 19.5 to 37.5 mm were taken July 7. A 70.0 mm specimen reported upon by Beebe (1941) was taken from the Florida coast on August 12, and the 208.0 mm specimen reported upon here was taken off Fort Lauderdale in March. It would be interesting from this to speculate upon the rate of growth of young sailfish but the data available are entirely insufficient to warrant it.

Investigations concerning the maturity of gonads were carried out at the Laboratory from 1950 to 1953 by Melvin Light, Winfield Brady, and H. P. Mefford. Results of this study are as yet insufficient to make any valid statements. Present indications are, however, that spawning may take place from spring through to late summer. Fe-

males with what were considered to be apparently mature eggs have been taken from April through to August, and males with mature testes have been taken as early as April. About 40 gonads have been examined to date.

Apparently the number of eggs spawned by a female is very large. Roes from ripe females often attain a length of 20 inches and weigh up to about 8 pounds. Mr. Harald Cahn gave the laboratory a gonad from a 72 pound sailfish which was 1312 grams in weight (about 3 pounds). By quantitative sampling, it was determined that the total number of eggs in the gonad was about 2,317,000. Some later investigations suggest a figure of around 4,675,000 eggs. From such a large number of eggs it may be seen that the mortality rate among the eggs and young is very high.

FOOD AND FEEDING

Apparently there is nothing in the literature dealing with the food and method of feeding of the Atlantic sailfish, with the exception of a single reference by Beebe (1941). As a result of this lack of knowledge concerning one of Florida's most important marine fish, the Marine Laboratory, in 1951, set up and carried out for several years an investigation of sailfish stomach contents in cooperation with various smoked fish houses and taxidermy studios, the actual work being carried out by Brady and Mefford. While no complete report on this has been issued by the project some of the data have been given in Quarterly Reports of the Marine Laboratory to the Florida State Board of Conservation. The following information concerning the food of the adult fish is taken from these reports; the information concerning the food of the young is from the authors' own studies.

All of the post-larval and juvenile specimens reported upon in the first part of this paper were later dissected and the stomach contents examined. As was expected the food of the earliest stages primarily consisted of copepods. Beebe (1941) has made some interesting comments upon this subject and gives a quote from Dr. Charles B. Wilson concerning the stomach contents of a Florida specimen of 70.0 mm standard length. In this quote Dr. Wilson suggests that the food of all of the younger stages of fish is copepods. In Beebe's specimen the copepods were listed as 1 *Oncaea* sp.; 1 *Oithona* (male) sp, and 15 *Farranula rostrata*. The copepods removed from the young in this paper were not identified as they were fragmentary.

Table 2 lists the stomach contents of the post-larval and juvenile

specimens examined by the author. The numbers correspond to those given earlier in the paper.

TABLE II.
STOMACH CONTENTS OF 13 POST-LARVAL AND JUVENILE
SPECIMENS OF SAILFISH, *Istiophorus americanus*

<i>Specimen No.</i>	<i>Standard Length in mm</i>	<i>Contents of Stomach</i>
No. 1	3.9	4 copepods
No. 2	4.8	1 heteropod, 9 copepods
No. 3	5.5	4 copepods
No. 4	6.3	1 larval fish, 5 copepods
No. 5	8.0	2 copepods
No. 6	15.0	Empty
No. 7	19.5	1 17 mm. Gonostomid
No. 8	20.0	2 small fish larvae, 1 copepod
No. 9	20.5	1 fish (halfbeak?) 10 mm. long
No. 10	29.5	1 fish larva 8 mm. long
No. 11	37.5	2 fish eyes, about 6 calanoid copepods
No. 12	70.0	2 fish larvae (unidenti- fiable)
No. 13	208.0	1 halfbeak (<i>Hemiramphus</i>)

From this table it is seen that in the very small specimens the food is undoubtedly mainly copepods but with an increase of only a few millimeters the type of food changes and at a very small size, fish are a major item of their diet. It is interesting to note that the 19.5 mm specimen had in its stomach a 17 mm Gonostomid, which, allowing for the bill length of the sailfish, was nearly as long as the sailfish. This Gonostomid was in quite good condition and was folded back upon itself three times in order to fit it into the stomach of the young sailfish. It can readily be seen that the depth of the body in post-larval fish is greatly increased and distorted by the amount of food contained in the stomach if the measurement is made at the point of greatest depth in a gorged fish.

Table 3 gives the contents of 241 stomachs examined by the Marine Laboratory staff. Identification to species was made whenever possible by the investigators and bothersome specimens were referred to specialists for identification or confirmation. Mr. Luis R. Rivas was consulted on fishes while the author identified the cephalopods.

TABLE III.

STOMACH CONTENTS OF 241 ADULT SPECIMENS
OF THE SAILFISH, *Istiophorus americanus*

Scombridae (mackerels, etc.)		Total -	59
<i>Euthynnus alletteratus</i> (little tuna or false albacore)	35		
<i>Acanthocybium solandri</i> (wahoo)	1		
<i>Scomberomorus (regalus) (?)</i> painted mackerel)	1		
Hemirhamphidae (halfbeaks)		Total -	42
<i>Hemirhamphus sp. (brasiliensis?)</i> balao	16		
Exocoetidae (flying fish)		Total -	6
<i>Cypselurus heterurus</i> (Atlantic flying fish)	1		
Belonidae (needlefish)		Total -	25
<i>Ablennes hians</i> (flat needlefish)	2		
<i>Stronglura notatus</i> (common needlefish)	5		
Trichiuridae (cutlass fish)		Total -	14
<i>Trichiurus lepturus</i> (cutlass fish)	13		
Monocanthidae (filefish)		Total -	2
<i>Monocanthus hispidus</i> (common filefish)	2		
Tetradontidae (swell or blowfish)		Total -	1
<i>Lagocephalus laevigatus</i> (rabbit fish)	1		
Mugilidae (mullet, some undoubtedly bait)		Total -	10
<i>Mugil cephalus</i> (black mullet)	1		
<i>Mugil trichodon</i> (silver mullet)	1		
<i>Mugil curema</i> (silver mullet)	3		
Priacanthidae (Big eye)		Total -	1
<i>Priacanthus sp. (catalufa)</i>	1		
Clupeidae (Herrings)		Total -	19
<i>Sardinella anchovia</i> (Spanish sardine)	11		
Engraulidae (anchovies)		Total -	2
Carangidae (jacks)		Total -	43
<i>Decapterus macarellus</i> (mackerel scad)	7		
<i>Caranx ruber</i> (blue runner)	9		
<i>Oligoplites saurus</i> (leather jacket)	3		
Sparidae (porgies)		Total -	12
<i>Lagodon rhomboides</i> (pinfish)	12		
Balistidae (triggerfish)		Total -	2
<i>Balistes (forcipatus?)</i> (spotted triggerfish)	1		
<i>Balistes carolinensis</i> (common triggerfish)	1		
Coryphenidae (dolphins)		Total -	1

<i>Coryphaena hippurus</i> (dolphin)	1	
Triglidae (sea robins)		Total - 1
Pomatomidae (Bluefish)		Total - 2
<i>Pomatomus saltatrix</i> (bluefish)	2	
Gerridae (mojarras)		Total - 1
Gadidae (cod)		Total - 1
Myrophidae (worm eel)		Total - 1
Unidentifiable fish		Total - 138
Cephalopoda (octopods and squid)		Total - 77
Octopoda (octopods)		
Argonautidae (paper nautilus)		
<i>Argonauta argo</i> (paper nautilus)	15	
<i>Argonauta sp. (hyans?)</i>	1	
Stauroteuthidae		
<i>Grimpoteuthis (?)</i>	11	
Decapoda (squid)		Total - 49
Ommastrephidae		
<i>Sthenoteuthis bartrami</i> (flying squid)	29	

An examination of the figures and especially the totals give some idea of the numbers and occurrence of the organisms utilized as food by the sailfish. In an attempt to determine the main source of food these figures were converted into percentages of the total numbers of food. The results are rather surprising, especially to those acquainted with sailfish and the popular misconceptions of their food habits.

By numbers the most prevalent group is the fish which accounts for 83.2 percent of their food. It is interesting to note that 16.8 percent of their diet consists of cephalopods (octopods and squid) of which the majority were paper nautilus, *Argonauta argo*. Following in importance by families, in the fish, were the Scombridae (mackerel and tunas) with 12.8 percent, the Carangidae (jacks) with 9.4 percent, the Hemirhamphidae (halfbeaks or balao) with 9.1 percent and the Belonidae (needlefish) with 5.5 percent.

It should especially be noted that the two families of fish which are popularly supposed to be the major food of the sailfish are conspicuously low in numbers. The mullets (Mugilidae) which are used especially in the northern areas of the coast, Fort Lauderdale, Boynton Beach, Palm Beach, Stuart, etc., as the chief bait, accounted for only 2.2 percent (10 spec.) of the food and of these 10 specimens most of them can be accounted for in the stomachs as representing the bait with which the sailfish were caught.

The flying fish have long been considered a rather important source of food, highly sought after by the fish, and captains often remark that

sailfishing should be good due to the large numbers of flying fish seen in the vicinity, an observation singularly lacking in supporting evidence either by the presence of sailfish in such areas or the numbers found in the stomachs. In our examination the whole family of flying fishes is represented only by 6 specimen or 1.3 percent.

The fishes and other organisms fed upon by sailfish indicate that they are not restricted to surface feeding: sea robins (Triglidae) and gastropods mollusks, of which several opercula have been found in the stomachs, are bottom dwellers, in contrast to the needlefish and halfbeaks which are typical surface forms.

One of the cephalopods, *Grimpoteuthis* sp., is also a bottom dweller from rather great depths, while the presence of considerable numbers of the paper nautilus, *Argonauta argo*, a reef dweller, help to confirm the opinion that sailfish are not typical surface dwellers by habit. Several of the other groups of fish not enumerated here are midwater rather than surface forms.

Brady and Mefford have suggested that a periodicity in diet was observed in their studies on stomach contents. This periodicity in the type of food was interpreted directly by the prevalence of the particular type of food in the waters at that time, rather than a predilection for certain food by the fish. Thus for certain weeks anchovies would be found in masses in the stomachs and then would disappear to be replaced by needlefish. Observations of charterboatmen show this to be particularly true in the case of the anchovies or sardines.

The method by which sailfish obtain their food has been a subject of much discussion and anyone who has been sailfishing with a variety of captains will have found that even in the manner of taking a trolling bait there is much contradiction, one school of thought maintaining that the fish strikes the bait with its bill to kill it, the other school maintaining that the striking action of the bill is a delusion and that the fish crushes the bait in its jaws. Both probably are right in certain cases but there is no mention at all of actual observations of natural feeding by sailfish.

In taking the bait, usually trolled at several knots on the surface, the fish rises behind the bait, usually a balao or mullet but also frequently a bonito strip, and after looking it over approaches it from the rear. When within striking distance, the bill is seen to rise above the bait and appear to strike at it with a downward or often a sidewise motion. Undoubtedly at times this is actually an attempt to stun or kill the bait with the bill, but more often the sailfish is attempting to

take the bait directly into its mouth to crush it and the appearance of the bill over the fish is a necessity caused by the extreme overlap of the upper jaw. An examination of hundreds of baits by the author which have been struck at by sailfish indicates that in nearly all cases the bait had been partly crushed between the jaws and scales were missing from both sides of the body where the jaws had closed over the bait.

In the fall and winter of 1940, during one of the greatest concentrations of sailfish known, off Stuart, Florida, the author had many opportunities of observing very closely and completely the action of sailfish in schools of bait and their method of obtaining them *in situ*. During that winter the sailfish gathered in unprecedented numbers off this famous sailfishing resort to feed on large numbers of small clupeid-like fish which were loosely termed by the fishermen "pilchards."

Apparently no feeding was done at night for in the early morning the fish were scattered. Around 9:00 the first schools began to appear as the sailfish, numbering from 6 or 8 to 25 or 30 began to mill about small groups of "pilchards," forcing them into compact schools by slowly circling about them at the surface, their sails half raised. While feeding the sailfish were oblivious to their own danger and a boat could be eased down into the mass of circling fish until often the sailfish would actually bump against the sides of the vessel. In this situation the author was able to observe frequently the actual method of feeding.

At short intervals, while the "pilchards" were kept bunched up by the circling sailfish, a single sailfish would break out of the circle and swim rather slowly directly through the small school of "pilchards," thrashing vigorously sideways with its bill, hitting fairly large numbers of the small fish stunning or killing them. After thrashing through the school, the sailfish would then turn, swim slowly downward beneath the school where it would then swim about picking up the dead "pilchards" as they sank downwards.

It would be impossible to estimate the number of sailfish gathered at Stuart at this time, nor the numbers of schools of the "pilchards" upon which they were feeding. During the feeding period, however, numberless schools of sailfish could be sighted by the great flocks of gulls, terns and pelicans assisting in the feast. The pelicans often became so excited that they dived upon the sails of the sailfish ripping the extended membrane leaving the rays of the dorsal fins standing.

Besides such methods of feeding as that described above sailfish are

frequently taken while fishermen are fishing the reefs in deep water with live bait. That this could be a very productive method of catching sailfish, can be inferred by the fact that in the stomach analysis the false albacore, *Euthynnus alletteratus*, a favorite live bait, accounted for 7.6 percent of all the food found.

It appears that in normal feeding, sailfish are usually rather slow and deliberate in their actions and sudden bursts of speed are the exception rather than the rule. Much has been written by various authors concerning the speed attained by sailfish and most authors agree that the sailfish is one of the fastest swimmers among fish, reaching a speed of 60 miles per hour. To this statement, the present author strongly disagrees and suggests maximum speeds of 25 to 30 miles per hour for this fish in short bursts of exertion. The speed of boats and fish at sea are subject to great exaggeration by even professional seamen and critical observations suggest speeds of over even 20 miles per hour for a sailfish as being unusual.

MIGRATIONS AND DISTRIBUTION

The first comprehensive account of the distribution of *Istiophorus americanus* is that of Goode (1883) which summarizes the records known at this time. According to Goode, the first account of the genus (and supposedly the species) is that of Piso and Marcgrave (1648) in "Historia Naturalis Braziliae" where a specimen is recorded from Brazil. This was given the name *Guebucu brasiliensibus* by Marcgrave and is considered by Goode to be the source of the name "Boohoo" by which this and related fish were called by sailors in the tropical Atlantic. This name was changed to *Histiophorus americanus* by Cuvier and Valenciennes (1831) and thus the type locality of our species is Brazil and the species is based upon the figure given in Piso. Much more work is necessary before it can be stated with certainty that the Brazilian fish and that of the coast of Florida are the same species.

If we accept Lutken's specimen as pertaining to this species and the validity of Marcgrave's record, the southern limit of the species as known extends to the vicinity of Brazil in the south and halfway across to the African coast (Gunther). Sanzo's (1930) identification of his specimen from Messina with that of Lutken's thus would include the Mediterranean in its range. According to Norman and Fraser (1949), a single specimen was taken in 1928 in Devon, England and there are records of its occurrence from Woods Hole, Massachusetts and from

the Gulf of Maine, although these are evidently those of stragglers.

In our own region they are frequently caught in the western Bahamas, although never in the numbers found in Florida. Along the east coast of the United States, they are most frequently caught from the Florida Keys to Daytona Beach, in the summer, with the heaviest year around concentration from the keys to just north of Stuart. They are also caught, although not in large numbers, with increasing frequency in the last few years along the North and South Carolina coast and they are now of some importance in the sport fishing off Morehead City.

Because of the skill, and rather specialized equipment required in sailfishing, the ranges of this species are very incompletely known but as new areas along our Atlantic coast and especially in the Caribbean region are being opened to sport fishing, much greater knowledge of their distribution and habits may be expected. At present, based only on adults and frequency of capture, thus disregarding occurrence of occasional stragglers and uncertain young, the distribution of *Istiophorus americanus* may be said to extend from northern South America throughout the Caribbean, the Gulf of Mexico, Florida, the western Bahamas and the Atlantic coast of the United States to Cape Hatteras.

The east coast of South America is very incompletely known as far as its fish fauna and ranges are concerned and attention should be turned to this area in future work with the bill fish. North of Cape Hatteras, the occurrence of sailfish is sporadic and appears to be determined in a large degree by the weather conditions. Long warm summers with southerly winds appear to bring the sailfish farther north than short cool summers with northerly winds, but even so they never occur in any numbers.

The occasional appearance of sailfish in northern waters and the increase of reports and landings along the Carolina and Virginia coasts have perhaps led to the theory that sailfish migrate over rather large areas. According to Baughman (1941), there is a migration of sailfish along the Texas coast for he states, "The earliest recorded occurrence of Texas sailfish in the spring is May 2, 1938. The latest appearance in the fall is November 11, 1939. Both these dates are from Port Idabel. The earliest date on which they were reported from the Freeport-Galveston area was late May, 1935, when one was reported from the Heald Bank, off Galveston. The latest appearance from the same area is September 7, 1937. These dates for the northern

area are unusual, for as a rule they do not reach this part of the coast till the early part of June. Beginning with this period, however, they are present throughout the entire summer." While this may apply to the Texas coast, it would seem to the author that the sportfishing industry for this fish is so new that the occurrences are based on too few boats and too short a time to be conclusive.

In the Florida area, even among many of the boatmen, it has been considered for many years that the sailfish is a migratory animal, occurring in southern Florida during the winter and migrating northward during the summer. This was a natural assumption by the fishermen in comparing the number of sailfish brought to the dock during the winter with those landed during the summer. Unfortunately, however, it has only been during the few years following the last war that any number of charterboats have fished Florida waters during the summer months, formerly going north to fish for white marlin along the Maryland coast and tuna off New Jersey and New York.

In the last few years an increasingly large number of charterboats are finding it economically more profitable to remain in Florida waters the year round. With the increase of boats in the summer months, it is proving to be remarkably good sailfishing during the calmer summer months along the Florida coast, and summer landings have risen remarkably.

From conversations with charterboatmen and from personal observations over some years it is the author's opinion that there is no regular migration or migrational pattern carried out by sailfish along the Florida coast. Instead, there is a year around breeding population or populations along the Florida coast which, within certain bounds, occupy much the same area the year around. During the winter months, beginning with the first cold northerlies in November, the sailfish appear in schools on the surface, running southward with the dorsal lobes of their tails at or above the surface. They continue to school in rather sizable numbers during cold northerlies throughout the winter months, but when warm periods or changes of wind occur they disappear, probably breaking up into individuals or pairs to feed over a rather large area from the Florida Keys to Fort Pierce. During this period they are seldom found on the surface except when jumping, although with certain bait conditions they may be attracted to a single area as in the aforementioned schooling in 1940 off Stuart which occurs off this place sporadically.

From early spring through the summer months, no schooling is

exhibited but sailfish are plentiful although scattered and unusual catches of 10 to 15 fish a day such as are made during the schooling periods are not found.

With the approach of summer and the extension of warm water to the northward there appears to be a diffusion, not a migration, of part of the border population to the northward along the inner edge of the Gulf Stream. During this period, single or several fish may be carried great distances accounting for the rare records of these fish in the vicinity of Cape Cod.

With the onslaught of cold weather in the fall, the fish which have been scattered along the coast, are driven southward by the northerlies to regroup along the Florida coast. As early as 1883, Goode remarked upon the role which temperature plays in the distribution of the swordfishes and the mackerel family (Scombridae), with which the Istiophoridae are closely related, and suggests that the critical temperature is above 50 degrees Fahrenheit, the fish avoiding temperatures below this point.

While we know that the king mackerel and tunas migrate out of this area during the summer months, in contrast to them, the sailfish are found in only slightly decreased numbers throughout the summer and we are unaware at present of any data concerning critical temperatures for these fish.

In an attempt to solve some of the perplexing questions concerning the movements and growth of these fish, the Marine Laboratory at the request of the state of Florida and in conjunction with other interested sporting groups, initiated a tagging program in 1949, using first a wire-on bill tag and later a common gill opercle cattle tag. Attempts at tagging bill fish and particularly the Pacific sailfish, *Istiophorus greyi*, have been made in the past but no returns have been recorded. This was particularly interesting in that several thousand fish had been tagged in Lower California waters without a single return.

It was therefore a matter of some importance when the first tagged sailfish was caught March 15, 1951 off Palm Beach. A check of the data showed that the fish had been tagged January 28, 1951 off Stuart, Florida by Ernest Lyons. This confirmed the opinion that sailfish tagging was feasible, and a later return of another tag showed that in a period of 13 months between time of tagging and recapture this later fish had only moved along the coast a distance of 43 miles. At present four tagged fish have been recovered from four hundred and ten tagged individuals.

Since this paper was written, renewed tagging activities by the Marine Laboratory, carried out by Robert H. Young, have resulted in over 200 tagged fish over a period of two months. The tag presently in use is a neoprene rubber ring which is rolled down over the bill of the fish and bears a monel tag. No results have been obtained since this tag was adopted and in the short time which has elapsed since the new program was initiated.

SUMMARY

1. The validity of the name *Istiophorus americanus* for the Atlantic sailfish is discussed and five species are recognized tentatively: *Istiophorus americanus* Cuvier and Valenciennes, Atlantic; *I. immaculatus* (Ruppell), Indian Ocean and Red Sea; *I. greyi* Jordan and Hill, Peru to Lower California; *I. orientalis* (Temminck and Schlegel) Japan and Hawaii; and *I. brookei* Fowler, from Tahiti.

2. Figures and measurements are given of 13 larval, post-larval and juvenile specimens of *I. americanus* ranging from 3.9 to 208.0 mm. standard length from Florida and the western Bahama islands, and graphs are given illustrating the gross morphological changes occurring through growth. These changes are discussed and it is shown that three stages of post-larval, juvenile and adult are clearly depicted by peaks of character change.

3. Post-larval specimens are characterized by short, thick bodies, short snouts with nearly equal jaws equipped with prominent teeth, large eyes and strongly developed pterotic and preopercular spines. The large dorsal fin is not in evidence until around 15.0 mm standard length. This stage reaches a peak of development at between 6.0 to 7.0 mm.

4. Juvenile specimens are characterized by extreme slenderness of body with a depth of about 7.0 percent of the standard length and a snout length of nearly 42.0 percent of the standard length. This stage is reached at about 70.0 mm and extends to about 300.0 mm.

5. Adult proportions are reached at around four to five feet and the transition from juvenile to adult is not marked by any distinct change.

6. From a study of the present series, it seems doubtful if Lutken's and Gunther's early stages of sailfish are referable to our species based on their descriptions and published figures.

7. From the date of capture of the present specimens, examination

of gonads and observations upon presumed spawning, the period of spawning in the Florida coast is considered to extend from May through August with a peak during June and July. The fish apparently spawn near shore in shallow water.

8. The number of eggs spawned by a female, from gonadal studies, is quite large. Ripe gonads have yielded egg counts of from 2,317,000 to 4,675,000 eggs.

9. The food of the earliest specimens, based on stomach contents, is first basically copepods but at a very small size (6.3 mm standard length) fish appear in the diet and these appear to predominate after a size of about 15.0 mm.

10. The stomach contents of 241 sailfish have been examined by Brady and Mefford. These studies indicate a predominance of fish in the diet but 16.8 percent of the total diet consists of octopods and squid. The most important families of fish in the diet, by numbers, were Scombridae (12.8%), Carangidae (9.4%), Hemiramphidae (9.1%) and Belonidae (5.5%). Flying fish were represented by only 1.3% or six specimens and mullet by 2.2%. Examination of the fish eaten indicates that the sailfish is not exclusively a surface feeder but also feeds on bottom dwellers and mid-water forms.

11. The method by which sailfish take trolling baits is discussed and observations of natural feeding in schools of bait is described. While the bill is used for killing or stunning small schooled bait, larger fish, particularly trolling bait are more often seized directly between the bony jaws.

12. The distribution of the Atlantic sailfish is considered, excluding single records of solitary stragglers, to extend from northern South America, the Caribbean, Gulf of Mexico to Florida, the western Bahama Islands and northward to Cape Hatteras. Brazilian records appear to be based upon Piso's figure (1648) while individuals taken in the vicinity of Cape Cod and the Gulf of Maine appear to be summer stragglers.

13. No definite migration occurs in sailfish along the Atlantic coast, although a northward diffusion occurs during the summer months along the inner edge of the Gulf Stream. During long hot summers with prevailing southerly winds individuals may be carried farther to the northward than commonly occurs.

14. Small migrations or movements due to weather changes are well known. These follow a general pattern. During periods of cold

northerly winds, especially from November through April, the sailfish school and are found running south on the surface. With a change of wind to the east and south, the sailfish disappear and scatter, concentrating in areas with plentiful bait fish.

15. Sailfish are found in lower Florida coast throughout the year in considerable numbers but due to summer diffusion, they appear to be slightly less at this time. With an increasing number of boats fishing during the summer, landings during this period compare favorably with winter landings.

16. Tagging of sailfish has been attempted in various parts of the world with no success. At the present time, four hundred and ten sailfish have been tagged and four have been recovered. One fish tagged was recovered 13 months later 43 miles from its tagging locality.

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